Fault Tolerant Virtual Backbone for Minimum Temperature in In Vivo Sensor Networks

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***Abstract*—Body sensor nodes those are implanted inside human body for comparatively long term monitoring, are termed as implanted or implantable or in vivo sensor nodes. In recent years, in vivo sensor nodes are getting increasing interest from clinicians or researchers around the world. These nodes are non-invasive and can provide more accurate information in terms of medical science being implanted on/near the targeted body-organ. Moreover, movement of human or body organ does not affect the functionality of in vivo nodes. However, in vivo sensor nodes exhibit temperature at processing or communication time, which might be dangerous for human tissue in long term monitoring. Thermal aware routing algorithms have been proposed to deal with the problem. But, these algorithms suffer from limitations like hotspot creation, computational complexity, delay etc. A virtual backbone is a small subset of connected sensor nodes and it is connected to all other sensor nodes of the set. All virtual backbone nodes involve less interference, congestion and lightweight communication those are significant for an in vivo sensor network. In this context, we have proposed fault-tolerant virtual backbone construction algorithm to schedule temperature(routing cost) in an in vivo environment. Fault-tolerance virtual backbone is significant in the sense that when any node or nodes of a in vivo virtual backbone has/have higher temperature, the path is disconnected and communication is continued with an alternative path. Therefore, temperature is scheduled in an in vivo sensor network.**

I. Introduction

Body sensor networks [1] have the potential to change the medical diagnosis system. One example of it is an vivo sensor node that is deployed in artificial retina, glucose monitoring, insulin pumps, blood pressure monitoring etc [2][3]. In vivo sensor nodes generate temperature when they transmit or process packets [4] [5]. In long term monitoring, these generated heat can be very harmful for patients. Moreover, these nodes are powered by battery which is recharged by IR (infrared ray). The more the Infrared ray is exhibited; human tissue becomes sensitive for bacterial attack. Existing thermal aware routing algorithms [3][6][7][8][9] for in vivo sensor nodes suffer from problems like hotspot creation, packet delivery delay, maximum hop or computational complexity. Existing communication protocols for sensor network (for example: directed diffusion [10], omniscient multicast or flooding techniques are not also applicable to this type of network [11].

A virtual backbone(VB) [12] is a subset of nodes in a sensor network. All other nodes are connected to VB and graph induced by these nodes is also connected. Only VB nodes are responsible for routing in this type of network. So, once a VB is established, it is very easy to deploy any conventional routing protocol in that network. As the number of nodes involved in routing is reduced, less interference, collision occur in the network. Connected dominating sets (CDSs) [12][13][14] are frequently used to construct the minimum VB in a wireless network. A connected dominating set(CDS) of a graph G is a subset D such that every node in G is either in D or adjacent to a node in D and the graph induced by D is connected. Nodes of D and G-D are called dominator and dominate respectively in a VB. Fault tolerance is very important for in vivo VB nodes. Because, they carry the routing information of other in vivo nodes. In an implanted sensor network, in vivo nodes may create a hotspot by continual operation for a long time. Therefore, to avoid hotspot, VB nodes can be frequently changed. However, data or link loss is a common feature for undefined physiological reasons. Therefore, to make VB nodes more resilient to volatile wireless network, fault tolerant VBs are very important in implanted sensor network. m-connected k-dominating sets are general representation of fault tolerant VBs. m-connected ensures that there are at least m different paths between any pair of dominators in a VB. k-dominating ensures that every dominate is connected to at least k dominators. Therefore, if we have a VB, constructed with m-connected k-dominating set, it is fault-tolerant upto m-1 disconnections of dominators and k-1 disconnections between a dominator and a dominate in vivo sensor nodes.

In this context, we have proposed a centralized algorithm InVivo-CDS-FTR to construct fault-tolerant virtual backbone with minimum temperature routing cost in an in vivo sensor network. Our contribution in this paper is as follows- (a) InVivo-CDS-FTR algorithm (section IV) with theoretical analysis(section V) and performance evaluation (section VI) (b) Survey (section II) on limitations of existing in vivo thermal aware routing algorithms those motivate us toward lightweight, fault-tolerant virtual backbone based solution (c) Application scenario (Section VII) with in vivo lightweight publish-subscribe that is deployed by fault-tolerant virtual backbone ,constructed with proposed InVivo-CDS-FTR. In our example scenario, this schedules temperature for in-vivo sensor nodes deployed for the joint operation of hyperthermia, radiotherapy and chemotherapy in cancer treatment [15].

II. Motivation for Lightweight, Fault Tolerant Virtual Backbone for Temperature Scheduling in In Vivo Sensor Networks

With the advancement of in vivo sensor nodes and wireless technology, communication protocols have also been proposed for temperature scheduling in an in vivo sensor network. These thermal-aware routing algorithms suffer from limitations like hotspot creation, complexity overhead or delay etc. TARA [8] was an early approach on thermal aware routing for implanted a sensor network. It is a routing protocol that sends packet by following a withdrawal strategy. If defines a hotspot region that is above a threshold value of temperature. When a node sends a packet to a hotspot, it withdraws from it and the packet is back to the sender. After the cooling period, the packet is sent again to destination. The protocol does not consider the shortest path, just only withdraws packet from hotspot. In LTR[6], packet is sent to next node if it is destination. Packet is generally sent to the node that has the least temperature. If the number of hops increases above a threshold value, the packet is discarded. If the next node is already visited then the second minimum temperature node is selected for packet transmission. ALTR[6] is an advancement of LTR. Packet is sent to the least temperature node but if the number of hops is increased above threshold value, SHR is followed in packet transmission. HPR[9] uses shortest hop routing algorithm for sending packet to the destination which does not have any hotspot. If the next hop is the destination, packet is sent to it. If the next hop has temperature below a threshold, packet is sent to it. But if the next hop is above a threshold temperature, it is assumed that there is a hotspot there. Then packet is forwarded to the coolest neighbor that is not yet visited. The problem with the HPR [9] is that temperature information has to be propagated to other nodes and it is a huge overhead. LTRT [7] has tried to solve the problems involved in previous algorithms. It tries to send packet through a path which creates the least temperature from the source to destination. The algorithm uses dijkstra algorithm to determine the shortest path from the source to the destination. It avoids hotspot formation and redundant multi-hops. The problem with the algorithm is that temperature information is to be propagated to every node with a regular interval. After the shortest path is created, the function of temperature schedule is established. Maintaining dijkstra algorithm is a huge overhead for an implanted sensor network

Limitations of these thermal aware routing algorithms have inspired us for lightweight, fault-tolerant virtual backbone based solution for in vivo sensor networks.

III. Definitions

In this section, we introduce different notations and definitions.

Notations: Let, G be Graph, V(G) be vertices of a graph G, E(G): (u, v) be an edge of a graph G, M be maximal independent set, D be Connected Dominating set, I be independent set, UDG be unit disk graph

Definition 3.1: Unit Disk Graph (UDG): A unit disk is a disk having diameter one. A unit disk graph (UDG) is a set of unit disks in Euclidian plane. We assume that each node is in the center of a unit disk. An edge E(u,v) exists between two nodes u and v, if disks associated with u and v intersects each other. So, we can conclude to following Lemma.

Lemma 3.2: An edge E(u,v) exists between two nodes u, v in UDG if and only if distance between u and v is at most one.

Lemma 3.3: Communication model between two nodes u, v is UDG if u and v have same transmission range and their distance is less than transmission range.

Proof: When all sensor nodes are identical and they have same transmission range, two sensor nodes can communicate each other if and only if their distance is within the communication range (disk with certain radius). It is isomorphic to a unit disk graph. ■

Definition 3.4: Dominating Set: D(G) is a dominating set of G if ∀v∈G, either v∈D(G) or ∃u such that (u,v)∈ E(G)

Definition 3.5:Connected Dominating Set: D(G) is a connected dominating set of G if (a) D(G)⊆V(G) is a dominating set of G and (b) graph induced by D(G) is connected.

Definition 3.6:Independent Set: I(G)⊆V(G) is an independent set of G if ∀(u,v), no edge exists between u and v

Definition 3.7:Maximal Independent Set: An independent set M is a maximal independent set if no v∈(G-M) can be added to M. If any v∈(G-M) is added, it is not an independent set anymore.

Definition 3.8:k-dominating set: A dominating set D(G)⊆V(G) is k-dominating if ∀v∈V(G)-D(G), v is adjacent to at least k nodes in D(G)

Definition 3.9:m-connected dominating set: A dominating set D(G)⊆V(G) is m-connected if graph induced by D is m-connected. It means that D is connected after m-1 dominators are removed.

Definition 3.10:Cut vertex: A vertex v∈V(G) is a cut vertex if graph G-v is disconnected

Definition 3.11:Block: A block is a maximal connected subgraph of G that does not have any cut-vertex.

Definition 3.12:Leaf Block: A leaf block of a connected graph G is a subgraph such that it is a block and contains one cut-vertex of G.

Definition 3.13:Good point: A vertex v∈V(G) is a good point, if subgraph induced by G-v is still 2-connected.

Definition 3.14:Bad point: A vertex v∈V(G) is a bad point, if subgraph induced by G-v is not 2-connected.

Definition 3.15: m-connected k-dominating set in unit disk graph with guaranteed routing is a combinatorial optimization problem

Given a unit disk graph G(V,E) and two positive integers m, k. Find a subset D ⊆V(G) such that (a)each vertex v∈(V(G)-D) is k-dominated by at least one vertex in D such that guaranteed routing[3] is maintained (b)D is m-connected

Every set satisfying (a) and (b) are m-connected k-dominating set.

Algorithm 1 InVivo-CDS-FTR

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Round 1: MIS Construction
INPUT: Color all nodes as WHITE node
Choose a node with maximum cardinality and select as root of MIS and color it as BLACK.
Color the neighbors of MIS node as GREY node
while There is no WHITE node do
        Choose the WHITE node that has the most grey neighbors and color it BLACK as MIS node
        Color the neighbors of new created black node as GREY
end while
OUTPUT: BLACK MIS nodes and other GREY nodes
Round 2: 1-connected 1-dominating set construction
INPUT: initially D is empty and BLACK MIS nodes, GREY nodes are present
for Every pair of BLACK nodes u and v with d(u,v)<=4 do
        Compute shortest path p(u,v) and color all intermediate GREY nodes of p(u,v) as BLACK
        Add u, v and intermediate nodes to D
end for
OUTPUT: D contains all BLACK nodes (MIS and connected nodes)
Round 3:1-connected k-dominating set
INPUT: 1-connected 1-dominating set
Remove MIS from the graph,G= G-M_1
for i=2 to k do
        Construct M_i in G-M_1 ∪ M_2 ∪ ...M_i − 1
        D= D ∪ M_i (Following Round 2)
end for
OUTPUT:1-connected k-dominating set
Round 4:2-connected k-dominating set
INPUT:1-connected k-dominating set
Find all blocks in 1-connected k-dominating set
while D is not 2-connected do
        Compute all blocks in graph
        Add all intermediate nodes of shortest path that (a)connects leaf block in D to other part of D (b)does not have any nodes in D except two endpoints
end while
OUTPUT:2-connected k-dominating set
Round 5: 3-connected k-dominating set
INPUT:2-connected k-dominating set
while There is no badpoint do
        Convert bad point to good point by moving from G-D to D, such that no new bad point is created
end while
OUTPUT:3-connected k-dominating set
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Fig. 1. Proposed InVivo-CDS-FTR Algorithm

IV. Proposed InVivo-CDS-FTR Algorithm

In this section, we propose InVivo-CDS-FTR algorithm for fault tolerant virtual backbone construction in in vivo sensor networks considering routing cost. The algorithm constructs m(<=3)-connected k(<=3)-dominating sets with routing cost constraint. InVivo-CDS-FTR is a round based algorithm. At first, MIS is constructed in unit disk graph model in an in vivo sensor network(Round 1). Then, nodes are connected to MIS nodes to construct 1-connected 1-dominating set considering guaranteed routing concept [13](Round 2). Then, subsequent *k*-1 MISs are added to CDS to construct 1-connected *k*-dominating set (Round 3). 1-connected *k*-dominating set is iteratively augmented to construct 2-connected *k*-dominating set [14](Round 4). At last, 2-connected CDS is turned to 3-connected by turning all bad points to good points using the strategy of [12](Round 5). As a result, InVivo-CDS-FTR produces *m(<=3)*-connected *k(<=3)*-dominating sets.

V. Theoretical Analysis

Lemma 5.1: MIS M is created after round 1 of InVivo-CDS-FTR.

Proof: In round 1, when a node joins M, its neighbors are colored gray. Next, unexplored white node joins M. So, there is no possibilities of gray node to join MIS. So, no two neighbors are included in M. Also, round 1 ends when there is no white node. So, there cannot be any node left to be added to MIS M. So, MIS M is created after round 1 of InVivo-CDS-FTR. ■

Lemma 5.2: [13]Let, G is connected graph and D is dominating set. Assume, for any pair of nodes u, v with d (u, v) =2,d_D(u, v)<=α +1
So, for any pairs of distinct nodes u and v, d_D(u, v) <= α d (u, v)

Lemma 5.3: [13] Let, G is connected graph and I, D are maximal independent set and dominating set, respectively. Assume, I is a subset of D such that for any pair of vertices u, v in I with d(u,v) <4, d_D<=4 So, for every pair of distinct nodes u and v d_D (u, v) <= 5d(u, v)

Lemma 5.4: CDS D is created after round 2.

Proof: At round 2, all intermediate grey nodes in the shortest path of two MIS nodes u,v (where d(u,v)¡4) are colored black . Lemma 5.2 and 5.3 yield that those black nodes (intermediate nodes and MIS nodes) construct connected dominating set. ■

*Lemma 5.5:*1-connected k-dominating set is created after round 3.

Proof: Let, G, D, I be connected graph, connected dominating set and maximal independent set respectively. After MIS and then CDS construction in first two rounds, k-1 subsequent MIS are added to CDS in third round. As a result of it, G-D nodes are k dominated by D nodes. That means each node of G-D is connected to k nodes of D. So, 1-connected k-dominating set is found. ■

Lemma 5.6: 2-connected dominating is created after round 4.

Proof: At the end of round 4, all dominator nodes are in same block, so that dominators are 2-connected [14]. So, we get 2-connected k-dominating set at the end of round 4. ■

Lemma 5.7: If vϵG is a good point, subgraph G- {v} is 2-connected.

Lemma 5.8: A 2-connected graph without any bad point is 3-connected.

Proof: A graph G is 3-connected if we need to remove at least three nodes to disconnect G. For example, v be a good point in 2-connected graph G'. From Lemma 5.7, G'-(v) is still 2-connected. So, we need to remove at least 2 nodes to disconnect G'. So, we can say G' is 3-connected. ■

Lemma 5.9: 3-connected dominating is created after round 5.

Proof: In round 5, all bad points are converted to only good points by transferring some nodes from non-dominator set to dominator set. At the end, 3-connected 3-dominating set is created [12] ■

VI. Performance Evaluation

In this section, we have conducted simulation to evaluate the performance of proposed algorithm. In simulation, in vivo

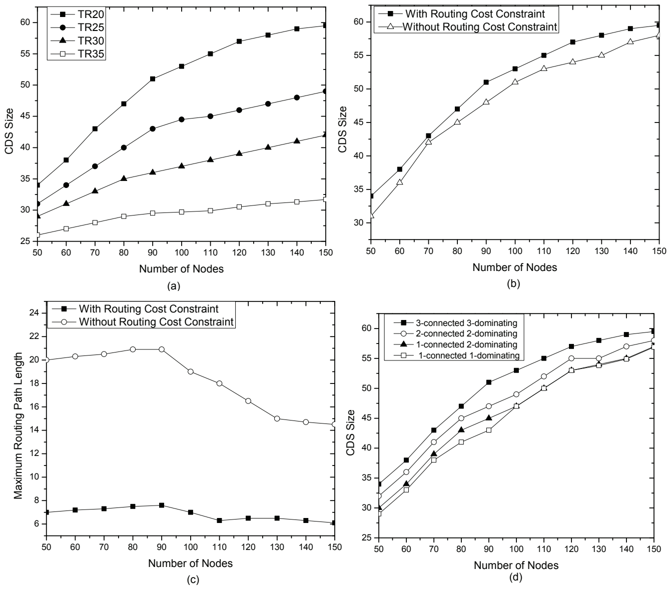

Fig. 2. (a)Changes of CDS size with increase of number of nodes for different transmission ranges. Impact of routing cost constraint on (b)CDS size and (c) maximum routing length . (d)Impact of fault-tolerance on backbone size

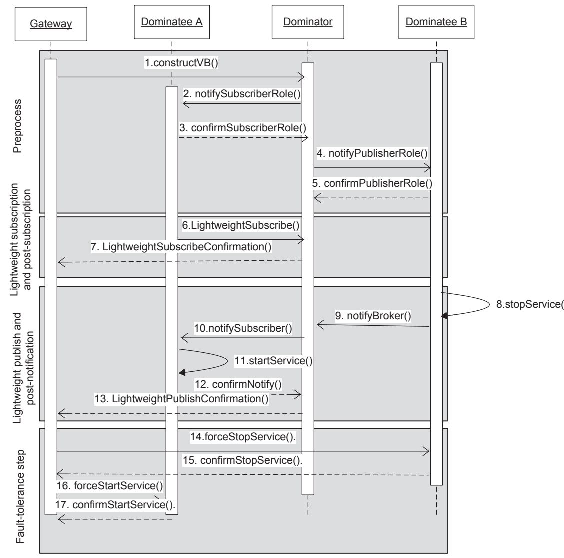

Fig. 3. Proposed In Vivo Lightweight Publish/Subscribe Routing

nodes are randomly deployed in a 100*100 plane. The number of nodes ranges from 50 to 150. 100 connected in vivo sensor nodes are randomly generated in this simulation setup.

A. Impact of transmission range and network size on backbone size

Fig 2(a) shows how backbone size changes with changes in transmission range and network size. As the transmission range increases, CDS size decreases. Because, CDS node can dominate more non-CDS nodes and we need few nodes to construct CDS. As the network size increases, CDS size increases. Because, we need bigger CDS to dominate non-CDS nodes.

B. Impact of routing cost constraint both backbone size and maximum routing length

Fig.2(b) shows the impact of routing constraint on backbone size. When network size increases, 'With routing cost constraint' generates larger backbone than 'without routing cost constraint'. Because, it needs more nodes to add to CDS to generate shortest path in CDS for node pairs' outside CDS.

Fig. 2(c) shows the impact of routing constraint on maximum routing length. 'With routing cost' generates less 'maximum routing length' than 'without routing cost'. Because, in 'with routing cost', a node has the high probability to connect to more neighbors that does not increase routing cost. So, routing cost constraint increases backbone size, but decreases maximum routing cost for every node.

C. Impact of fault-tolerance on backbone size

Fig. 2(d) shows how backbone size is changed with change in fault-tolerance. When, backbone has no fault-tolerance (1-connected 1-dominating set), backbone size is the minimum. Gradually, when make 1-connected 2-dominating set, we need to add one more MIS to CDS. So, with improvement of fault-tolerance, CDS size is increased as well. When we make 2-connected 2-dominating set, we need to augment the backbone by adding nodes to connect leaf block in the backbone to other block/blocks. As a result, backbone size increases. When we make 3-connected 3-dominating set, backbone size increases as well. There are two reasons for that. Firstly, non-CDS nodes have to move to CDS to convert bad points to good points. Secondly, more MIS nodes have to be added to CDS.

VII. An Application:Lightweight Publish/Subscribe in In Vivo Sensor Nodes

In this section, we have proposed an in vivo lightweight publish/subscribe system (Fig.3) that can be deployed with the help of fault-tolerant virtual backbone that is constructed with proposed InViVo-CDS-FTR algorithm. As the proposed InVivo-CDS-FTR is a centralized algorithm, we have considered that a gateway communicates with in vivo nodes to construct virtual backbone. Gateway then communicates with in vivo nodes in a lightweight way as described below.

At first (Fig 3.), gateway node notifies dominator in vivo sensor nodes about their VB construction information (Step 1). Dominator node then sends subscriber and publisher roles to dominate nodes (Step 2-5). At lightweight subscription (Step 6-7), subscriber nodes subscribe to a dominator node. The dominator node then sends subscription confirmation message with the list of successfully subscribed nodes, to the gateway node.

At lightweight publish (Fig 3.) (Step 8-13), when an event occurs, the publisher stops related service and then sends notification message to dominator and dominator then forwards it to subscribers. Subscribers immediately start related service and immediately notify the dominator. The dominator also

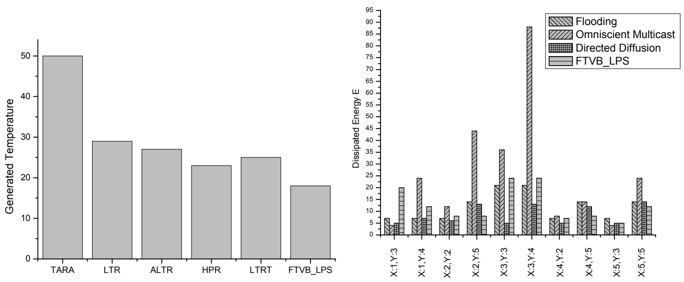

Fig. 4. Comparison of In Vivo Lightweight Publish Subscribe(denoted by VBLPS) with (a) existing thermal aware routing algorithms and (b) data dissemination techniques namely directed diffusion, flooding and omniscient multicast

sends notification confirmation to the rendezvous node. The gateway node then checks in the VB whether all the subscribers are successfully notified. If they are not notified due to packet loss from publisher to dominator or from dominator to subscriber or from dominator to gateway node, the gateway directly communicates with subscribers and publisher to start and stop their service immediately (Step 14-17).

A. Performance comparison

Fig. 4 shows that proposed in vivo lightweight publish-subscribe mechanism, denoted by VBLPS in figure, outperforms thermal aware routing algorithms and traditional data dissemination techniques in terms of temperature generation and energy dissipation.

B. Implementation Scenario

In cancer treatment, the joint operation of hyperthermia, radio- therapy and chemotherapy has become the most prominent [15]. It depends on the temperature generated on human cells. If the temperature is below a threshold temperature, hyperthermia enhances performance of radio-therapy and chemotherapy. But, if it is above the threshold, human cells become sensitive and it becomes dangerous to human health. We are consider- ing in vivo sensor nodes reflecting temperature scheduling in join operation of cancer hyperthermia, radiotherapy and chemotherapy. If the temperature of a node (publisher) is increased above threshold, it will communicate broker node to disseminate temperature to subscriber node or nodes. If the temperature dissipation is not performed successfully, remote gateway node should be notified by broker node.

VIII. Conclusion

In this paper, we have proposed algorithm to construct lightweight, fault-tolerant virtual backbone to schedule temperature in in vivo sensor networks. In example scenario, this algorithm can schedule temperature in in vivo sensor nodes deployed in cancer treatment with hyperthermia,radiotherapy and chemotherapy.

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