Energy-efficient Priority-based Routing Scheme for the Healthcare Wireless Sensor Networks
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Abstract: - In time-critical and data intensive applications, efficient acquisition of sensitive datasets is a challenge because of network congestion, void regions and node failures that commonly occur in wireless sensor networks (WSN), while monitoring the wellbeing of patients with serious medical conditions. The sensor devices attached to such patients are used for monitoring the vital signs of those with serious heart problems, Parkinson disease, Epilepsy and high blood pressure. This paper typically focuses on the reliable acquisition of datasets and provides a fault-tolerant priority based routing scheme with Dynamic Jumping (FTMPR-DJ) for the energy-efficient acquisition and dissemination of datasets. A new fault-tolerant scheme has been proposed that will significantly minimize data loss and network congestion and is well supported with extensive experiments to show effectiveness of the proposed routing scheme.

Key-Words: - Wireless sensor networks, Energy-efficient, fault-tolerant, priority-based routing, network latency, context-sensitive

1 Introduction

Fault-tolerance is crucial for the real-time monitoring of sensitive situations that frequently occur in real life; therefore, dissemination of sensitive datasets needs to be efficiently communicated to the sink node. In medical emergencies, the presence of faults due to communication link error, node failure and void regions can be life threatening. Wireless Sensor Networks (WSN) [20 - 37] are widely used in Healthcare, habitat monitoring, battlefields, earthquake, fire, medical emergencies, transportation of goods, weather forecasting, home and office security monitoring [1 - 6]. This thesis typically focuses on how to achieve the desired functionality in sensor networks during the presence of faults due to malfunction of a particular node because of some errors at the hardware level, software layer, network level, congestion and broken communication links [22] etc.

The existing fault-tolerance techniques and protocols [2 – 6] and [8 - 9] provide a routing of datasets through multipath or hop-by-hop manner to some extent, but do not properly address the issue of data loss and network state after the malfunctioning of a node. In WSN, real-time acquisition of dataset is a challenge because of the presence of void regions created due to the node failure. Bypassing such regions cannot provide a reliable solution to such problems, because it leaves the network in a highly unpredictable state in real-time and mission critical applications such as healthcare, where the breakdown of communication is not only life threatening but would also leave the network in a situation where data loss would be beyond the acceptable threshold. Such situations are widely ignored by the existing fault-tolerant protocols and schemes discussed in [2 – 6], [7 -10] and [11].

This research extends the protocol discussed in [2] and [5] and typically focuses on shortcomings of the approach discussed in [3] and proposes a new hybrid fault-tolerant scheme, that not only provides the real-time acquisition of datasets but also provides a reliable communication by adjusting the probability of jumping when it is absolutely necessary and will also significantly minimize the energy consumption by setting the priority of routing packets through a certain path using a multi-sink approach [2-4].

The proposed scheme is discussed in the methodology section in detail to show the effectiveness of the approach; two parallel aggregators near the sink nodes are also used to reduce the communication overheads from the upstream and downstream nodes, which are also discussed in the methodology section.

Section 2 discusses the related work; section 3 provides a detailed analysis of the proposed approach and routing scheme to describe this model.
Section 4 provides the overview of fault-tolerant situation analysis and further elaborates on the shortcomings of existing fault-tolerant algorithms. Section 5 provides the simulation results in terms of comparing the proposed approach with existing fault-tolerant schemes for efficient energy consumption reliability and data loss are discussed in [2], [4], [5], [13], [16]. Section 6 discusses the experimental analysis with scenarios necessary for understanding acquisition of datasets in the healthcare wireless sensor networks. Section 7 provides an overview of probabilistic path selection in sensor networks. Section 8 provides a detailed analysis of the proposed FTMPR-DJ scheme. Section 9 discusses the conclusion and future work.

2 Related Work

Real-time fault-tolerance is an active area of research in WSNs and very few protocols and algorithms have been designed to address the fault-tolerance in healthcare sensor networks. Healthcare monitoring is a sensitive domain and acquisition of relevant datasets is crucial for the survival of patients with life-threatening conditions. Existing algorithms and techniques for routing datasets of interest use either Roving Networks (RN-42) or IEEE802.14.6 communication protocol [17], [24], [31] for the dissemination of data to the sink node, but fault-tolerant aspects are widely ignored in the existing research literature. Below is the overview of protocols that provide fault-tolerance to some extent but are not properly used in the healthcare domain. The proposed research provides a detailed analysis and extensive support for the fault-tolerant related issues in the healthcare domain that is crucial for the survival of patients.

RPAR (Real-time Power-aware Routing) protocol was proposed in [2], [3], [4] and [5] for the dynamic adjustment of nodes transmitting datasets with respect to energy consumption, but the node failure was not taken into account in order to achieve the desired functionality in the presence of faults. Similarly, in [4] QoS routing protocol [10], [12] is proposed but energy consumption and node failures are ignored while transmitting datasets of interest in the resource constrained environment. Constrained equivalent delay (CED) is used for the dynamic selection of next hop so that path selection can be simplified from the source to the sink node.

In [9 - 11], SPEED (Stateless Protocol for Real-time Communication in Sensor Networks) was proposed which estimates the transmission rate between the current node and sink node before routing packets through a particular path. SPEED-T and SPEED-S were also proposed, which selects the forwarding candidate set [FCS] by looking at the minimal transmission delay between the upstream and downstream nodes. The upstream node is that node which is a few hops away from the sink or destination node and the downstream node is the opposite of that. The problem with this approach is that the network congestion and void regions are ignored and the ideal situation for minimizing the time delay was considered. In [10], MMSPEED (Multi-path and multi-level SPEED Routing Protocol) sets up a tree structure by looking at the distance between the current node, next hop and the sink node before routing datasets of interest. The main problem with this approach is that the time complexity of estimating the node reachability is also not suitable for the large-scale, distributed and long-distance communication.

In [5], DMRF (Dynamic Jumping Real-time Fault-tolerant Routing Protocol) was proposed where each node utilizes the remaining time of the datasets to be transmitted. Before transmitting data packets FCS (forwarding candidate set) state is monitored for the network congestion, void regions and faulty nodes if it exists then the transmission mode will automatically be adjusted to jumping so that a packet can be routed to the sink node without any delays. The facts that are widely ignored by the DMRF protocol are: the distance of node from the sink, estimation of the possibility and the selection of node according to the jumping probability based on the certain threshold value can significantly reduce the possibility of reliable communication in the real-time, fault-tolerant wireless sensor networks. The proposed approach in this thesis looks at fault-tolerance at various levels because of the sensitive nature of the healthcare domain where data loss can be life threatening for patients with high blood pressure and serious heart conditions.

The proposed FTMPR-DJ approach focuses on ensuring reliable and fault-tolerant communication, which is crucial for the well-being of patients in the healthcare domain. Details about the proposed approach have been discussed in the Methodology section.

2.1 Preliminaries

The healthcare wireless sensor network is a sensitive domain, which specifically focuses on monitoring the wellbeing of patients with serious medical conditions. The work done in [11] and [12] has been extended in several respects such as:-
The sensor nodes discussed in [11] and [12] were stationary whereas in our application scenario nodes can move because sensors are attached to patients with serious medical conditions. If the patient moves at a certain distance ‘d’ within the communication radius ‘r’ then a message will be transmitted through a node closer to the sink. The mesh network topology is used for better energy consumption by minimizing the data loss that usually occurs if the path from source to sink is greater than the communication radius or a faulty node exists in the path closest to the sink. Parallel aggregator nodes are used closest to each sink, in case if the first aggregator malfunctions then the other aggregator gets activated for transmitting datasets to the sink. The node probability ‘p’ will be set to dynamic jumping ‘DJ’, if aggregators (Ai, Aj) closer to the sink malfunction due to void region, link or node failure. Fault-tolerance in the healthcare sensor networks is an active area of research but very few efforts are made to explore the fault-tolerance in detail. Several aspects of node failures are tested with respect to the four conditions mentioned above. This research also extends algorithms mentioned in [2], [5] and explores the performance in terms of network congestion, void regions, link and node failures. Reliable communication is important for the monitoring of a patient’s health condition, while disseminating data to the sink node. This research typically focuses on transmitting datasets of those patients with Parkinson disease, Epilepsy, high blood pressure and with the serious heart conditions.

### 3 Proposed Methodology

Fault-tolerance is critical in the healthcare sensor networks in terms of monitoring vital signs of patients with serious medical conditions. This research focuses on the energy efficient acquisition of data from patients with heart disease, Parkinson disease, Epilepsy and fall detection in elderly patients with Arthritis.

The proposed Fault-tolerant Priority based Routing with Dynamic Jumping (FTMPR-DJ) scheme shown in the Figure 1 typically depicts the multipath and multi-sink routing scheme for the dissemination of datasets to the nearest sink. The protocols discussed in [2], [4 - 5] are extended and the hybrid dynamic jumping scheme is proposed, which provides an extensive level of fault-tolerance for minimizing the data or packet loss problems in the body area sensor networks. Node mobility also causes failure, if the node is moving in and out of the sensing range. The proposed scheme balances the energy consumption before routing datasets or packets to the nearest sink; therefore, the path with the better energy consumption will be selected before routing packets. In Figure 1, paths will be selected from the point ‘P’ to the nearest sink using the multipath scheme. If the path is broken due to node or link failure, an alternative path will be selected as discussed in [2 - 3] and priority will be set to the point ‘P-1’. The chances of link failure, void regions and network congestion is fairly common where the sensor nodes are attached to several patients and acquisition of datasets is crucial for their survival. It is also assumed that some patients require multiple sensor devices for monitoring their well-being. Therefore, a loose strap to their body or a fall can increase the number of faulty nodes. The proposed scheme uses double priority points from where paths can be established to the nearest sink and data will be transmitted to through multipath. Idea of multi-sink [3] is extended for enhancing fault-tolerance and multi-path scheme [3 - 4] is used to ensure that alternative paths can be selected while routing datasets of interest to the nearest sink.

**Figure 1.** Fault-tolerant FTMPR-DJ Scheme

The proposed FTMPR-DJ scheme shown in Figure 1 is different from [5] in several respects. Besides, the multi-path and priority based routing “Dynamic Jumping” is introduced for enhancing fault-tolerance, which is shown in Figure 2 to further elaborate the concept of jumping probability. Here
probability of the node will be set to jumping only when the sensing radius and the distance of the node closest to the sink have a broken link or a faulty node. Feedback mechanism similar to DMRF [5] protocol is used to determine the status of the next hop.

Sensor devices attached to patients constantly transmit enormous amount of data; therefore, the battery consumption of a sensor node will be significantly increased. An aggregation scheme similar to the directed diffusion [26] is used for reducing the communication overheads. The aggregation schemes are shown in Figure 3 and Figure 4, which looks at duplicate sensitive datasets so that unnecessary routing of similar packets can be reduced for a better throughput. The diagram also shows if the aggregator is faulty, then data can be routed through the parallel or alternative aggregator. The proposed scheme will significantly increase fault-tolerance by efficiently monitoring the energy consumption, which in case of faulty node transmission will be set to jumping by effectively looking at the probability and distance of the node from that particular point to the nearest sink (Si).

It is also to be noted here that S1, S2, S3, ............, Sn-1, Sn are the sensor nodes deployed in the certain sensing range ‘r’ at a distance ‘d’ from the next hop. Similarly, A-1, A-2, .... Ai-1, Ai are the aggregators responsible for transmitting datasets to the sink node. Two parallel aggregators are used closest to the sinks so that transmission cannot be disrupted because of the node failure or faults.

Figure 2. Dynamic jumping probabilities

Figure 2 above depicts a similar scheme to the one mentioned in [5], where the transmission was set to jumping due to a link failure and faulty node. The jumping probability will be set before routing packets to the nearest node or sink. In the proposed scheme, probability will only be set to jumping when it would be extremely necessary for avoiding data loss.

The proposed algorithms discussed in this thesis provide high level fault-tolerance by efficiently balancing the energy consumption of nodes before routing packets to the nearest sink. In [3], [5] focus was on routing packets to the next hop but widely ignored the fact that routing nodes might have broken links or node failure. Therefore, the main challenge would be to achieve a desired level of functionality in the presence of fault. Similarly in [5], dynamical jumping ‘DMRF’ protocol was proposed but focus was on the residual energy and a quick decision to route packet by looking at the FCS (forwarding candidate set), network congestion and void regions but did not explain about the impact on network in case of more malfunctioning nodes and the routing scheme only proposed a single sink. Therefore, the approach discussed in [4 - 5] does not provide a high level fault-tolerant solution, which is required to achieve the desired functionality in case of node, link or sink failure.

The hybrid PBR algorithm with dynamical jumping is proposed that typically focuses on:

a) Balancing the energy consumption before selecting a particular path.
b) Looks at the node or a link failure so that data can be routed towards an alternative path to the nearest sink.
c) Dynamical jumping mode will only be selected if the probability of reaching to the nearest sink or node is very high.
d) Parallel aggregators near the sink node are used for removing duplicate sensitive datasets for a better throughput and low energy consumption.
e) Healthcare sensor networks is the focus of the proposed approach, therefore high level fault-tolerance is required for monitoring wellbeing of patients with serious medical conditions.

As discussed in [5] and in our previous research publications [4]. Equation (1) represents the path ‘P’, which is defined as the set of all nodes at a certain distance ‘D’ from the Sink-i, where V(Ai), V(Aj) are the parallel aggregators for enhancing fault-tolerance and equation (2) is for calculating the overall energy consumption cost.

$$P = \{V_{s1}, V_{s2}, \ldots, V(A_i), V(A_j), V_{sink-i}\}$$

(1)

There the communication cost can be defined as:
\[ \text{Cost-P} = \sum \frac{\text{Econ}}{\text{Cost (Di,j)}} \]  

(2)

If \( \text{Econ} = 0 \), it means that the path is broken due to some node failure.

The following equations shown below are discussed in exactly the same manner in \([4, 5]\). Equation (3) shows the total number of transmissions required to find datasets of interest from sink to the source at a distance \( (r – 1) \) hop, and can be calculated as shown below, which is similar to the model discussed in \([4,5]\), where ‘Ni’ represents the node with relevant information.

\[ \text{Transmission} (T) = 1 + \left[ \frac{d}{r} \right] \left( 1 + Ni + r \right) r^2 + d \]  

(3)

Equation (4) shows the number of transmissions from source to sink at a distance ‘d’ would be equal to the equation shown below, where \( Ni \) is the node with an answer to the relevant query.

\[ \text{Total-Transmission} (Tt) = (1 + r^2 Ni + r) \left[ \frac{d}{r} \right] - 1 \left[ 1 + 2r^2 Ni + r \right] + d \]  

(4)

Therefore, the probability that the transmission would be successful for the node in the critical path would be equal to the following equation (5), which is similar to the equation mentioned in \([4, 5]\); where \( Ni \) is the arbitrary node with the relevant datasets. Value of the malfunctioning node would be between zero to \( R(\text{max}) \), \( \frac{Pf}{2} \) represents the probability of a malfunctioning node within a particular path.

\[ \text{Probability} (P(Ni)) = \prod_{i=1}^{d} \left[ 1 - \frac{Pf}{2} \cdot R(\text{max}) - f \left( \left( \left\lfloor \frac{d}{r} \right\rfloor - i \right) r \right) \right] \]  

(5)

Algorithm-1 shown below represents that the paths to the nearest sinks are created from the node ‘P’. The Routing table (RT) has the source and destination address of the next hop and the critical path to the sink node. It also looks at the minimum cost of routing datasets of interest to the nearest sink through an alternative path depending on a particular threshold value. Node state and sink_ID will be returned in case of broken link; if the path energy consumption is zero then an alternation path with the minimum energy cost will be selected for reliable communication.

3.1 **Algorithm 1** Faulty node detection and sink_id selection with the minimum cost.

1. Input: node ‘P’ and the routing table (RT)
2. Output: sink_ID, node state and path with the minimum cost
3. Begin
4. If the source node P is not faulty
5. Calculate the cost of routing to the nearest Sink(i)
6. If the cost is more than the specified threshold (\( \alpha \))
7. Select an alternative path to sink (i)
8. Else
9. \( \text{minCost} = \text{Cost of routing to the sink(i)} \)
10. Return sinkNode_id
11. Else
12. Return Node_state and (new)sink_id with minCost
13. End if
14. End if
15. End

Algorithm-2 shown below represents the priority based routing with dynamic jumping (FTMPR-DJ). The main purpose is to ensure the reliable communication in the presence of fault due to broken link or node failure. The proposed approach is different from \([8]\) in many respects such as: in the presence of fault, void regions or network congestion, data can be routed through a path with maximum energy level. The jumping probability \( [Jp] \) will only be utilized if there is a node failure near the sink and no other alternative paths available due to real-time acquisition of dataset and is also crucial to meet the deadline without compromising the quality of service. The node state parameter value will automatically be adjusted to the jumping mode due to sudden failure of a particular node. The proposed scheme also has parallel aggregators that ensure duplicate sensitive communication to avoid communication overheads. In case the aggregator node near the sink has failed, communication will automatically be adjusted through the parallel aggregator and the message will be broadcasted to all neighbouring nodes so that communication can be established through an alternative path.
3.2 Algorithm 2 Energy-efficient routing Algorithm with dynamic jumping mode adjustments (FTMPR-DJ).

1. Input: node ‘P’ and the routing table (RT)
2. Output: (new)sink_ID, NodeState and MaxPathEnergyLevel (EL)
3. Node state: Could be either void, congestion, faulty or jumping mode
4. Begin
5. If the source node P is not faulty
6. Calculate the cost of routing to the nearest Sink(i)
7. IF the path has fault-Node adjust the jumping probability ‘Jp’ to jumping
8. Only, when it is crucial to meet the deadline and no alternative exists THEN
9. Calculate MiniEnergy consumption for routing to the nearest node
10. IF the Energy level is more than the specified threshold (α)
11. Then no other node exists in the sensing range ‘r’due to void regions/congestions
12. Select an alternative path to sink (i)
13. minCost = Cost of routing to the sink(i) with better energy level
14. Return (new)sinkNode_id, with NodeState
15. Else
16. Return Node_state and (new)sink_id and MaxPathEnergyLevel (EL)
17. End if
18. End if
19. End

The jumping probability ratio equation will be very similar as mentioned in [8], as shown below.

\[ J_p(i) = \frac{\text{Success}_t}{\sum_{t=1}^{m} \text{Success}(t)}, \quad \text{where} \quad (t = 1, 2, 3, \ldots, m) \]  

(6)

If the node is in the transmission mode and did not get any reply then it means that the node is in the failure state and the mode will be adjusted to jumping and FCS (forwarding candidate set) will be adjusted accordingly. But the proposed approach efficiently looks at the energy consumption of the critical path before routing dataset to the nearest sink, if E(con) = 0, it means the link is broken due to the malfunctioning of a particular node in the FCS.

4. Experimental Analysis

This section provides detailed analysis of patients with serious medical conditions. It also looks at improving the current healthcare system by providing a new technique that will further improve fault-tolerance and acquisition of data from elderly patients who are not able to visit hospital quite often and remote monitoring would be the only solution to ensure their wellbeing. Detailed experiments are conducted on certain subjects of interest in the next sections and simulations are performed using LabView [30], MatLab[32] and the actual Shimmer [31] sensor platform for the acquisition of ECG, EMG and Gyroscope datasets from those patients where remote monitoring is crucial for their wellbeing and survival.

This research also provides real-time acquisition of datasets from those patients who have serious heart conditions, Hypertension, Epilepsy and Parkinson disease; therefore, it is necessary to monitor the electrical activity associated with muscle contractions, nerve condition and muscle response in case of injured tissues for the real-time acquisition of biomechanics of human movement related datasets.

This section also focuses on detailed experimental analysis of patients with serious heart conditions that require continuous monitoring of ECG (Electrocardiogram) and EMG (Electromyogram) to ensure the wellbeing of such patients. EMG, ECG, accelerometer and Gyro sensors are attached to those patients who are elderly and recording electrical activity of the heart and muscular contraction is crucial to be monitored for their survival.

For the acquisition of data, real-time analyses of patients are performed at various locations such as home as well as in the hospitals. Sensor devices are attached to such patients where the most recent electrical activity of heart and muscular contractions due to the movement need to be efficiently monitored and data can be transmitted to PC, Laptop or mobile phone as shown in the Figure 3.

The ECG (Electrocardiogram) sensors [31] are used for recording electrical impulses through the heart muscle. It can be recorded on the ambulatory subjects, during exercise sessions for the acquisition of information on the heart rate in relation to the physical exertion. EMG sensors are attached to subjects for recording the fall detection in elderly patients and are also used on subjects for recording electrical impulses or activities related to the
angular movements of patients with Epilepsy (Figure 4a and Figure 4b) type symptoms, which is shown in Figure 3a and Figure 3b and will be discussed in detail in the that particular section.
The simulation results below clearly show that the proposed FTMPR-DJ scheme has outperformed the existing fault-tolerant solutions [8 – 11] that are discussed above. Ratios of faulty nodes were studied with respect to the successful transmission of data packets. Similarly, the ratio of faulty-nodes and the network congestion was also observed Figure 11a, Figure 11b and Figure 11c; in all such cases our proposed FTMPR-DJ scheme has outperformed the existing solutions mentioned in terms of efficiently routing datasets of interest to the sink node.

In Figure 11a, the proposed scheme FTMPR-DJ was compared against the existing protocols and schemes such as Flooding, Priority-based Routing (PBR), FT-SPEED and the Dynamic Jumping (DMRF) protocol. The main purpose of this experiment was to monitor behavior of nodes in the presence of fault and also to test the effectiveness of the proposed Fault-tolerant scheme FTMPR-DJ.

5. Conclusion

The proposed routing scheme FTMPR-DJ was discussed in detail to ensure real-time and reliable acquisition of datasets from multiple sensor devices. The purpose of the proposed approach was to improve fault-tolerance in real-time acquisition of datasets in the healthcare sensor networks.

Simulation results show that the proposed scheme discussed above has outperformed in terms of efficiently transmitting datasets of interest, when routing datasets to the nearest sink node in the presence of node failure, network congestion and void regions. Simulations were performed using actual sensor devices as well as in the MatLab [32] and LabView [30] for testing the effectiveness of the proposed approach, whereas in DMRF [5], simulations were not performed in the dynamic real-time cluster-based environment. The proposed algorithms discussed above clearly show the effectiveness of FTMPR-DJ scheme in detecting, identifying and rectifying faults by efficiently balancing energy consumption before routing packets to the nearest sink. Extensive simulations were performed for the real-time acquisition of datasets, where the sensor devices were attached to the subjects of interest for monitoring, ECG, EMG, GYRO, fall detection and temperature, simulation results are discussed in Section 6 in detail. As a part of our future work, we are planning to test the proposed approach with a large number of sensor networks and devices that will further investigate fault-tolerance to minimize the network latency for better throughput.

References:


17. IEEE Standard 802.15.4, "Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)," 2006.


