A Real-Time Routing Protocol for (*m,k*)-firm Streams in Wireless Sensor Networks

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Abstract—**As a novel real-time application in wireless sensor networks (WSNs), multimedia transmission has posed a new challenge that both reliability and timeliness must be satisfied at the same time to support an acceptable quality of service (QoS). However, the inherent resource constraint of sensor nodes and instability of wireless communication make it not practical for existing routing mechanisms to meet the requirements of this QoS aware application. To address the problem, we propose an innovative protocol in this paper, for energy and QoS aware routing of (*m,k*)-firm based real-time applications over WSNs. The routing depends on optimal forwarding decision which takes into account of packet end-to-end deadline, node condition and remaining energy of next hop. A local status indicator (LSI), which was specially devised for (*m,k*)-firm stream, is used in the routing scheme for each node to monitor and evaluate its local condition. The proposed protocol has been well studied and verified through simulations. The results have proved the efficiency of the proposed routing protocol in terms of higher successful transmission ratio and smaller end-to-end delay.**

I. INTRODUCTION

The up-to-date technological advances in the domains of micro electro-mechanical systems and wireless communications have enabled the development of specifically featured and inexpensive applications in Wireless Sensor Networks (WSNs). The networks, which consist of large number of low-priced sensor nodes, have been promoted to extract more realistic and precise information of the fast-changing events in the real world [1], with the availability of enhanced nodes such as low-cost and miniature size cameras or microphones. These nodes can provide more power and functions to make it possible for WSNs to capture multimedia data, such as video and audio streams and still images in real-time applications. That is, in addition to scalar sensor data based traditional applications over physical phenomena like temperature, pressure and location of objects, the networks of wirelessly connected smart devices propose a new variety of time-critical applications for environment monitoring, animal tracking, and security surveillance, etc.

Multimedia data, generally regarded as real-time mission-critical data, must be treated more efficiently than non-real-time scalar data, for its application-specific quality of service (QoS) requirements. Therefore, routing techniques used in multimedia transmissions should consider not only energy efficiency and reliability, but also timeliness of received packets to facilitate specific service guarantee [1]. In general, real-time QoS guarantees can be categorized into three classes: hard real-time (HRT), soft real-time (SRT) and firm real-time (FRT). In HRT system, each packet will be checked with its deterministic end-to-end delay, named deadline, when it arrives at the destination. The arrival of a packet after its deadline is considered as system failure [2]. Due to the inherent constrains and lossy link connections of WSNs, it is impractical to guarantee HRT in WSNs. In SRT system, a probabilistic guarantee is required and some deadline missing is tolerable so that the time-out packets are still useful and system would not be crashed. Most existing real-time routing protocols are supposed to guarantee SRT in a hop-by-hop manner. FRT sets the criterion between HRT and SRT that the lateness of some packets is tolerable but it may cause system performance degradation at the same time. Considering the inherent features of WSNs and application requirements, FRT is the optimal QoS guarantee for real-time communication over WSNs.

In [3], an FRT model called (*m,k*)-firm was proposed to measure the performance of real-time applications. The concept of (*m,k*)-firm was defined that a real-time message stream is considered to have an (*m,k*)-firm guarantee requirement that at least *m* out of any *k* consecutive messages from the stream must meet their deadlines to ensure adequate QoS [3]. Based on this concept, a priority assignment technology called Distance Based Priority (DBP) was developed to arbitrate between the streams in a system. For each stream, the system maintains a state to capture the recent history of the deadlines met and missed. Then the state is denoted as DBP of the stream. When a stream is close to a failing state, i.e. one of the grey states in Fig. 1, its customer will give it a high priority so as to increase its chances of meeting the deadline.

Taking advantage of this model, we proposed a local status indicator (LSI) over WSNs to indicate the local condition of transmission status at each node. Unlike DBP assignment in [3], which was used for only one hop model, LSI is used in a multi-hop network. Moreover, LSI is aiming to evaluate transmission quality at each hop and to detect network faults instead of assigning priority to streams. To the best of our knowledge, there’s no existing similar works introducing FRT to real-time applications over WSNs. The main contribution of this paper is a real-time routing protocol which calculates optimal forwarding node based on three metrics: packet end-

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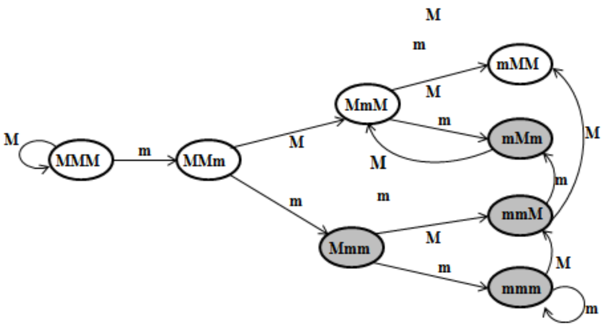

Fig. 1. State Transition Diagram Example of (2,3)-firm

to-end deadline, LSI which is regarded as node condition, and remaining power of sensor node. Since end-to-end deadline is used for node choosing, the QoS requirement is considered by each node. By choosing the forwarding nodes with qualified LSI, the real-time transfer is ensured. Additionally, awareness of remaining power avoids fast drain of energy on often-used nodes. The selection of forwarding nodes is supposed to guarantee required QoS of real-time application and subsequently prolong the lifetime of networks. The protocol shows high performance in terms of successful delivery ratio and deadline meeting, which have been studied and reported through simulations.

The rest of this paper is organized as follows. Some related works are summarized in Section II and the proposed routing protocol design is elaborated in Section III. Section IV shows the simulation results and analysis. We conclude the paper with open issues in Section V.

II. RELATED WORKS

The most common real-time routing protocols in WSNs are presented here. SPEED [4] is a well-known soft real-time routing protocol. It estimates the transmission speed between current node and candidate nodes, tries to establish a transmission path with all relay nodes maintaining a desired delivery speed. However, it doesn't take packet deadline of a real-time stream into account, which consequently leads to severe end-to-end dynamic failure. A multipath and multi-level SPEED routing protocol (MMSPEED) was proposed in [5], which supports service differentiation and probabilistic QoS guarantee. It dynamically selects the next hop according to the distance among the current node, neighbour node and sink, and sets up a tree structure with multipath for different QoS requirements of applications. However, the time complexity of this scheme is an exponential function of the distance between the current node and the sink node. Therefore, it is not suitable for large-scale long-distance transmission. RPAR (Real-time Power-Aware Routing) was proposed in [6], in which the node transmitting power is dynamically adjusted according to its transmission condition and capability. The forwarding node selection is based on the delivery velocities upstream node requires and downstream node provides. Energy consumption is considered as an important issue as well. A Scalable Hierarchical Power Efficient Routing (SHPER) was proposed in [7], in order to form an energy-efficient routing by electing the cluster heads according to the residual energy of the nodes. Based on it, authors of [8] developed an innovative routing scheme named Power Efficient Multimedia Routing (PEMuR) for WMSNs aiming at achieving considerable reduction of energy consumption during routing along with high perceived video QoS. A real-time routing protocol with load distribution (RTLD) was proposed in [9], which makes forwarding decision based on link quality, packet transfer velocity and remaining power of next hop, aiming to ensure high packet throughput and long lifetime of networks.

III. DESIGN OF PROPOSED ROUTING PROTOCOL

The main components of the proposed routing protocol are arranged as shown in Fig. 2. The routing protocol consists of three functional modules: neighbour node management, routing management and power management. The neighbour node management discovers a subset of candidate nodes and maintains a neighbour table to record useful information of forwarding candidates. The power management determines whether the current next hop is available for transmission or not, according to node's remaining power. The routing management selects optimal forwarding nodes, and makes forwarding decision.

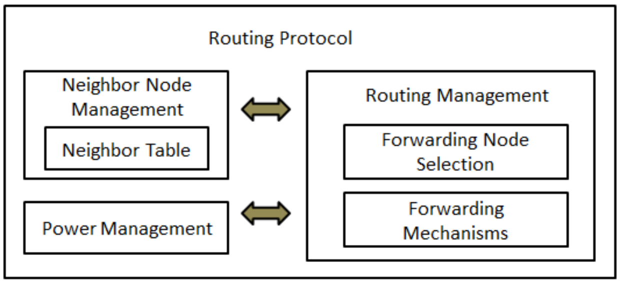

Fig. 2. The components of the proposed routing protocol

A. Neighbour Node Management

The neighbour node discovery procedure is based on the beacons each node periodically broadcasts to its neighbours. This periodic beacon contains location and remaining power information of nodes. In order to prolong the network lifetime, the remaining power of next hop is also considered as a metric for making forwarding decision, so that the energy of some overloaded nodes will not be drained much earlier than others. The details can be found in subsection *B*.

In addition to periodic beacon, one kind of on-demand beacons is also used to implement an important functionality. The stream DBP beacon is sent from sink to source node as a feedback during transmissions at a regular interval. The value of stream DBP is then added into the headers of generated packets by source node, and propagated to the intermediate nodes to help with making forwarding decisions. We argue that the communication overhead of neighbour node discovery is small. It is necessary to minimize the time it takes to discover forwarding candidate nodes.

The information provided by beacons is maintained in a neighbour table at each node, and updated over time. The entries of this table are shown as below: (*Neighbour ID*, *Position*, *EnergyLevel*, *ExpireTime*, ($m_{s(n)}$,$k_{s(n)}$), $Deadline_n$, $DBP_{s(n)}$). The *ExpireTime* is set to be a standard *RTT* (Round-Trip Time) of packet transmission between a pair of nodes. By the nature of WSNs, which all nodes could be source nodes and generate packets, node *n* records the (*m,k*)-firm requirement of its own stream, named ($m_{s(n)}$,$k_{s(n)}$). Also, the deadline of the packets generated by node *n* is marked as $Deadline_n$. The stream DBP value informed by stream DBP beacons is also recorded as one entry, named $DBP_{s(n)}$, to show the QoS of stream, which is generated by node *n*. The calculation is done by the equation presented in [3] as follows:

$$DBP_{s(n)} = k_{s(n)} - l_{s(n)}(m_{s(n),}s) + 1 \qquad (1)$$

where $DBP_{s(n)}$ is the measured DBP value of stream *n* at sink, $k_{s(n)}$ comes from the required (*m,k*)-firm of stream *n*, $l_{s(n)}(m_{s(n)},s)$ denotes the position (from the right) of the *m*th deadline meeting in the current state *s* of stream *x* [3]. When one packet is received, a 0 or a 1 is shifted in (from the right) depending on whether the packet missed or met its deadline. If there are less than $m_{s(n)}$ 1s in *s*, then $l_{s(n)}(m_{s(n)},s) = k_{s(n)} + 1$. For example, suppose stream *S(1)* has (1, 3)-firm deadline. Then, $l_{s(1)}$(1, MmM) = 1 and $l_{s(1)}$(2, MmM) = 3.

B. Power Management

The power management is responsible for energy awareness of sensor nodes in WSNs. It is used to avoid some often-used nodes from draining too fast. The node remaining power information obtained by periodic beacons, stored as *EnergyLevel* in neighbor table, is used to compare with a lower-threshold of remaining power, named e_{thd} in the proposed mechanism. Once *EnergyLevel* is observed lower than a pre-defined e_{thd}, power management would be activated to remove this node from the forwarding set. Therefore, the remaining power will be used for only sensing events, and processing the data generated by node itself. It can significantly reduce the probability of the appearance of network voids, and prolong the network time substantially.

C. Routing Management

The routing management contains two sub-functional processes: forwarding node selection and forwarding mechanism. The forwarding node selection is used to calculate the forwarding node set based on forwarding metrics. The forwarding mechanism is aiming to implement the forwarding process according to the QoS requirements and forwarding node conditions.

In order to figure out the optimal forwarding calculation, three forwarding metrics are considered: packet end-to-end deadline, LSI and remaining power of nodes. According to the information provided by subsection *A* and *B*, we can easily measure the first two metrics, packet end-to-end deadline and remaining power, through $Deadline_n$ and *EnergyLevel*, correspondingly. The last metric LSI, which is improved from an early form proposed in our prior work [10], works at each node to indicate the local condition. It is based on DBP assignment [3] which was used for only one hop model, but implements different functionality in a multi-hop network. LSI allows the intermediate node to investigate the local transmissions to the next hop. The value of LSI is calculated as follow:

$$LSI_{s(n)\_i} = k_{s(n)} - m_{s(n)} - c_{s(n)\_j} - f_{s(n)\_j} \qquad (2)$$

where $LSI_{s(n)\_i}$ stands for the distance to failure on node *i*, *k* and *m* are set as the value of required (*m,k*)-firm; $c_{s(n)\_j}$ and $f_{s(n)\_j}$ denote the congestion and link failure levels of downstream node *j*, respectively.

After an intermediate node receives the first packet, it starts a timer and forwards the packet to the neighbour nodes on its neighbour table. At the time this node receives ACK from the downstream node, the experienced delay is set to be a standard *RTT*, named *ExpireTime* as mentioned in subsection *A*, and stored into the corresponding entry of its neighbour table. Since it's possible that the nodes close to sink forward more packets than others, the *ExpireTime* would be longer there. Therefore, the *ExpireTime* is not the same for all nodes, but proportional to the number of hops from sink. After an intermediate node forwards a packet, it waits until the *ExpireTime* timeouts. The result of waiting is shown in Fig. 3.

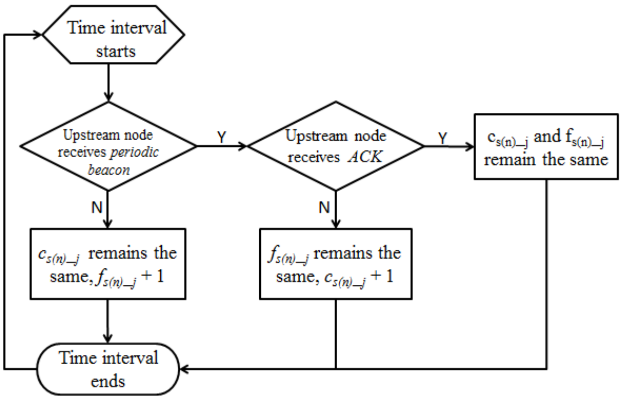

Fig. 3. Results of waiting within one time interval

Given by the three metrics of each downstream node, the upstream node could make forwarding decision, according to the following algorithm in Table I.

A 2-step algorithm runs at each time when the upstream node receives a packet. Step 1 is used to select a forwarding set from the nodes listed in neighbour table. The selection is based on the three forwarding metrics we mentioned before. If the end-to-end deadline from node *n* is smaller than the remaining time of received packet, it's possible for upstream node to forward the packet to node *n*. That is, it's possible that within $Deadline_n$ the packet could be delivered to sink. Also, the $DBP_{s(n)}$ must be checked that only if it is in positive condition, the $Deadline_n$ can be met. In other words, node *n* can guarantee that the packet would be delivered to sink within $Deadline_n$. Then the local condition should be checked.

TABLE I
ALGORITHM FOR FORWARDING MECHANISM

$Deadline_s$: end-to-end deadline of packet from source
$Deadline_n$: end-to-end deadline from node *n*
S_{node}: set of nodes in neighbour table
$DBP_{s(s)}$: stream DBP of packet from source
$DBP_{s(n)}$: stream DBP of packet from node *n*
$(m_{s(s)}, k_{s(s)})$: (m,k)-firm requirement of packet from source
$(m_{s(n)}, k_{s(n)})$: (m,k)-frim requirement of packet from node *n*
$LSI_{s(n)}$: LSI of packet from node *n*
S_{fwd}: forwarding set
$E_{rem,n}$: remaining power of node *n*
e_{thd}: lower threshold of power management

PSEUDO-CODE EXECUTED BY UPSTREAM NODE IN EACH ROUND

STEP 1

```
for there is node in $S_{node}$ do
begin
    if $Deadline_n <= Deadline_s$-elapse time then
        if $DBP_{s(n)} > 0$ then //guaranteed deadline from node n
            if $LSI_{s(n)} > 0$ && $m_{s(s)}/k_{s(s)} <= m_{s(n)}/k_{s(n)}$ && $E_{rem,n} < e_{thd}$
            //guaranteed LSI and remaining power
                then node n is in $S_{fwd}$
            end if
        end if
    end if
```

STEP 2

```
    if $S_{fwd} != \emptyset$ then
        if $DBP_{s(s)} > 0$ then //QoS in positive condition
            next_hop = arg_max{ $E_{rem,n}$ }
        else then
            next_hop = arg_max{ $LSI_{s(n)}$ }
        end if
    else then
        discard
    end if
end
```

To successfully forward a packet, LSI must be in a positive condition. Here's one thing to notice: even the values of LSI are the same, *(m,k)*-firm requirements may differ. It's possible that the required *(m,k)*-firm is stricter than the provided one, i.e. (3,4)-firm to (2,4)-firm, so the provided *(m,k)*-firm will not be considered even its LSI in positive condition. The remaining power of node must be guaranteed higher than the defined threshold as well. The nodes which can meet all requirements will be added to a forwarding set. By this combination of three routing metrics, both reliability and timeliness requirements can be met to enhance QoS performance.

In Step 2, optimal forwarding node will be figured out if the forwarding set is not empty; otherwise the packet would be discarded. In case that stream DBP of current transmission is in positive condition, which indicates its QoS requirement is met, the principle for next hop selection is energy efficiency, so that the node with largest remaining power would be the optimal forwarding node. In other case, the node with best condition, regarded as LSI, would be chosen.

IV. SIMULATION RESULTS AND ANALYSIS

Simulation results demonstrate the performance of the proposed routing protocol. We chose NS-2 as the simulator. 50 nodes are randomly placed in 200m X 200m field. 2 source nodes are randomly selected within an event area radius of 50m. Sink is located at the lower right corner of the field. Thus the end-to-end hop-count ranges from 4 to 7 hops with an average of 5 hops. Each node has a radio range of 50m. Propagation model is set to be Two-Ray Ground, protocols for physical and MAC layer are set to be wireless-phy and 802.11.

We set two scenarios to evaluate the performance. The first scenario makes one source node generate periodic traffic and the other source node generates aperiodic bursty traffic at times, to prove the adaptability of the proposed protocol, when facing a rapid change of data volumes. The second scenario contains various channel errors during transmissions in order to estimate the capability of QoS guarantee over unstable networks.

Evaluation results are presented as: 1) packets end-to-end deadlines missing ratio, 2) stream end-to-end dynamic failure ratio. The former one considers the delay of QoS requirements, and the latter one is supposed to measure the QoS in terms of both packet loss and jitter, which are the main reasons of dynamic failure in real-time applications.

A. Packets End-to-End Deadline Missing

Fig. 4 and Fig. 5 plot the packets end-to-end deadline missing ratio of 3 algorithms: SPEED, the proposed protocol with (3,5)-firm and (4,5)-firm guarantees. The packets end-to-end deadline is set to be 50ms for all 3 algorithms.

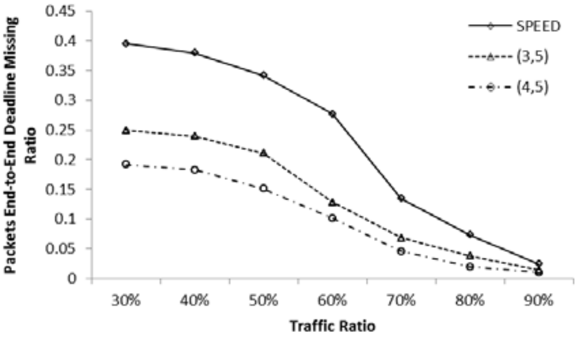

Fig. 4. Packet End-to-End Deadline Missing

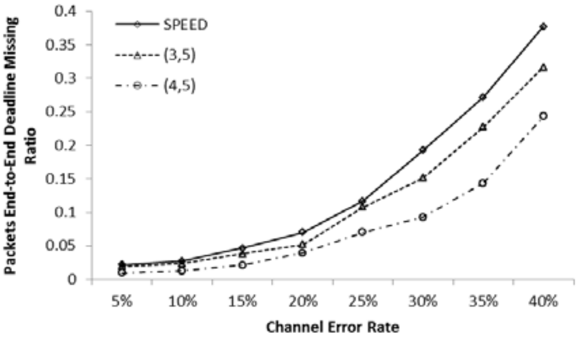

Fig. 5. Packet End-to-End Deadline Missing

We choose the periodic traffic as an evaluation target, thus the horizontal axis of Fig. 4 stands for the ratio of the target traffic to all traffics in network. When the percentage gets bigger, the network bears heavier traffic load. Especially for the nodes which are closer to sink, the probability of congestion occurring is much higher than other nodes. In Fig. 4 we can learn that the traffics transmitted using SPEED experience more than 25% packet deadline missing when traffic ratio is about 60% and almost 40% deadline missing when traffic ratio becomes 30%. Considering only delivery speed as the routing metric, SPEED cannot perform as well as the proposed routing protocol, which takes both application requirement and node condition into account for making forwarding decision.

We can get similar result from Fig. 5. In a scenario where channel error happens and increases proportionally, deadline missing ratio of SPEED rises dramatically since its forwarding is based on only transmission speed. On the other hand, even under unstable network condition, LSI works well to indicate the “distance to failure” of intermediate nodes. Also based on both LSI and stream DBP, the proposed routing protocol can efficiently react to errors and switch the next hop. The difference between (3,5)-firm stream and (4,5)-firm stream in Fig. 5 is that according to mechanism of LSI, (4,5)-firm stream has a stricter requirement, so that the upstream node is more sensitive to the transmission status changes, and it will make more agile reaction to change the downstream node with better condition.

B. *Stream End-to-End Dynamic Failure*

In Fig. 6 and Fig. 7, we evaluate the stream end-to-end dynamic failure ratios among 3 algorithms: SPEED, the proposed mechanism with different deadlines of 40ms and 50ms, respectively. We give a (3,5)-firm guarantee requirement for all 3 algorithms to test if they could meet their QoS guarantee.

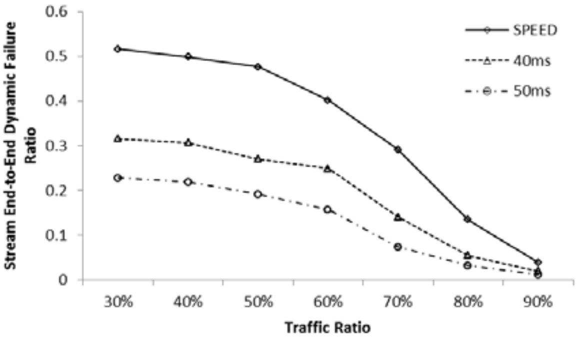

Fig. 6. End-to-End Dynamic Failure

We set the same horizontal axis for Fig. 6 and Fig. 7 as Fig. 4 and Fig. 5, respectively. Since in real-time applications, dynamic failure is caused by packet loss and jitter, the proposed routing protocol shows better performance than SPEED for its capability of reliability and timeliness. The significantly rising curves of SPEED in both figures demonstrate that without consideration of end-to-end deadline and node condition, it fails to supply good QoS performance in case of heavy traffic or instable network environment. Together with stream DBP, the proposed LSI plays a very important role in packets transmission that it makes all intermediate nodes to be aware of local transmission status with the next hop, and make correct decision on next hop selection. By distributing the duty of guarantee (*m,k*)-firm from sink to each intermediate node, the combination of three metrics and stream DBP together make it possible to keep good QoS performance of real-time applications.

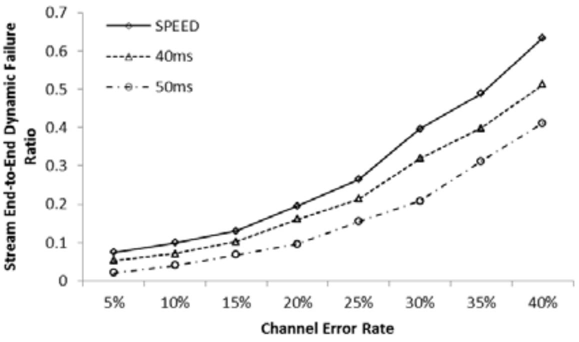

Fig. 7. End-to-End Dynamic Failure

V. CONCLUSION

For real-time applications such as multimedia data transmission in WSNs, efficient routing protocols are highly desired to guarantee QoS requirements of applications. Differs from existing works, the proposed routing protocol is responsible for both reliability and timeliness guarantees. It uses three routing metrics to calculate optimal forwarding node: packet end-to-end deadline, node condition LSI, and remaining power of next hop. The combination of these three metrics works with stream DBP, which is regarded as the QoS performance, to achieve a real-time and energy aware routing for multimedia applications. Simulation results demonstrate that in case of heavy loaded or unstable network conditions, the proposed protocol could show better performance than existing work.

The future work is focus on fault recovery mechanisms which can work with the proposed routing protocol.

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