Multi-modal routing to tolerate failures

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***Abstract*—Reactive routing protocols such as AODV (Ad-hoc On-demand Distance Vector routing) are commonly used routing algorithms in WSNs and use route discovery broadcast packet to establish route or recover from link failure. However, frequent route discovery can aggravate the congested network. Retransmission technique has been proposed in Not So Tiny (NST) AODV to reduce the number of route discoveries due to short sporadic link failure at the cost of memory consumption and packet delay. To address these issues, we propose a distributed Multi-mode Routing Protocol (MRP) that automatically switches between routing protocols (AODV and NST-AODV) in real time. Incorporating a timing-based route selection mechanism has reduced the numbers of routing packets generated. Results from extensive simulations have shown significant improvement on packet delivery ratio and power consumption with MRP.**

I. INTRODUCTION

Over the years, most existing works in WSNs have mainly focused on permanent failures due to malicious attacks and node movements [1]. In real world implementations, WSNs are usually static and network failures are usually caused by battery depletion, component malfunction, obstruction, and interference due to an external source. Little work has been done in failure detection and recovery in these areas. Transient network failures caused by interference are common in WSNs as they share the same radio frequency band with other radio emitting and home devices such as portable phones, microwave ovens, bluetooth devices, and Wi-Fi networks. Recent experiments performed by Hou et al [2] have shown significant packet loss of between 10% to 30% due to external interference. These failure durations and occurrence rate can differ from time to time, and is definitely not permanent where most effort has been previously applied to WSNs. Existing literature has revealed that no single routing protocol on its own can perform and handle all types of network anomalies [3], [4]. Each routing protocol has specifically been designed to tolerate specific network failure, and has shown better performance than others in a specific network condition.

This suggests that different protocols are used in different situations, which means at any one time, the overall network may be operating in multiple protocol. The work in this paper is based on Adhoc On-demand Distance Vector (AODV) [3] as it is widely acccepted and one of the most commonly used routing protocols. It can tolerate permanent node failure where no alternative route is available. However, if the networks are susceptible to sporadic frequent link failures, the control packet overhead may increase dramatically. Retransmission in Not So Tiny-AODV (NST-AODV) [4] is proposed to tackle failure caused by sporadic radio interference. However, this single retransmission can only handle short sporadic failures and may not be able to handle failures with different durations. Hence, the use of self-switching routing mechanisms in WSNs, where each node can dynamically change its routing algorithms based on the current network conditions and the anomalous characteristics, have been suggested.

In this paper, we propose a distributed Multi-modes Routing Protocol (MRP) that is implemented in individual nodes that can switch between two routing algorithms in real time depending on the type of anomalies. We are interested in recovering the network from anomalies caused by external sources. To the best of our knowledge, this is the first time that a solution based on enroute selection using multiple variants of AODV has been proposed to handle both transient and permanent failures in a static environment. The motivation behind re-using the existing known protocols is that we do not want to design a whole new protocol that is not supported by existing hardware. In contrast, what is proposed in this paper can be supported using commonly available hardware, e.g. MICAz, IRIS, and TelosB [1], [4]. We have also incorporated a stop and wait protocol [5] with a static window to handle the dynamic transient characteristics.

The main contributions of this paper are: 1) A novel timing based routing protocol selection methodology that positively selects an appropriate routing algorithm in real time to achieve better network performance; 2) A quantitative evaluation of our MRP, and comparison with existing WSNs routing protocols. The results have shown a significant improvement in the network performance compared to AODV and NST-AODV without MRP. The rest of this paper is organised as follows: Section 2 discusses related works. In section 3, we provide a detailed description of our proposed solution, and evaluated our proposed system, under the influence of transient failure with different failure durations and frequencies in section 4.

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In section 5, we summarise with our conclusions.

II. ROUTING IN WSNS

Many routing algorithms that have been developed for WSNs recently can be categorised into proactive, reactive and hybrid routing [6]. Proactive routing uses a simple flooding mechanism to broadcast their routing state to the entire network [7]. Nodes periodically monitor and update their routing table even when there are no packets to send. Due to the limited resources, proactive routing is less popular in WSNs as the routing table in a node can be very large in a dense network and frequent flooding consumes excessive energy resources. Reactive routing is a query based routing where a route is only established when required by the source. Reactive routing also uses a flooding mechanism. However, less energy is used for routing as sensor nodes always remain in an idle state until data transmission is required. Due to its *on demand* characteristics, reactive routing protocols have been widely used in WSNs.

Different reactive routing protocols have been proposed in WSNs to achieve certain network performance level. AODV is one of the widely researched reactive routing protocols in WSNs, originally proposed by [3] for mobile adhoc networks (MANET). A source node will flood the network with Route Request (RREQ) packets when it needs to transmit a packet to an unknown destination. Route Response (RREP) will be transmitted by the destination using the reverse route, allowing the source to select the shortest route to send the packets. During link failure, AODV will perform a local route discovery (RD) to determine alternative route to the destination if failing node is closer to the destination. In order to control the broadcast of RREQs, RD uses an expanding ring search mechanism [8] to manage the propagation of the RREQs. However, packets transmitted during RD usually have a higher latency as the network is usually more congested than usual. As sporadic and temporal link failure is common in WSNs, it can initiate unnecessary RD. Frequent RD consumes large amount of resources, reduces the lifetime of the network, and can aggravate a congested network. To avoid RD caused by sporadic, bad radio network condition, NST-AODV [4] has been proposed based on existing features of AODV that performs additional network layer packet retransmission to minimise network control packets generated by local repair. NST-AODV [4] has managed to reduce the network latency and increase the number of data transmitted, but additional memory is required to buffer the data packets, and its single retransmission can only handle short transient failures.

For the reasons above, alternative hybrid routing, with the combination of proactive and reactive routing, has been proposed in various literature to reduce delay and improve energy efficiency. The Zone Routing Protocol (ZRP) [9] is the first hybrid routing protocol where proactive routing is applied within a cluster of nodes and reactive routing is performed between clusters but it is unable to adapt to the dynamic topological changes created by external sources. A policy based approaches have been proposed in [10], [11] that can adapt to the behaviour of WSNs. [10] proposes a priority based hybrid routing that can switch between geographical diffusion and AODV depending on the packet priority for a specific application. [11] proposes a policy based adaptive routing in WSNs where a set of nodes can switch between reactive or proactive routing protocols depending on the forwarding policy. This policy based approach uses a centralised routing decision that will be made by the destination node based the network statistics observed and a threshold level. It is subject to single point of failure.

The solution proposed by [10] is application specific. Due to the differences in reactive and proactive protocols, the routing switching module proposed in [11] may cause service discontinuity when individual node switches from one routing protocol to another, to reset and reconfigure its routing service. Additional delay and overhead are required for a distribution mechanism to reach an agreement on the routing decision. Hence, we have proposed a solution based on purely reactive routing protocols where an individual node will make its own decision to switch between the routing modes autonomously with minimal disruption to network services.

III. DESIGN AND MODELLING OF MRP-AODV

To address the issues discussed above, we integrate the best existing features from various AODV protocols and operates in one of the feature modes depending on the characteristics of the network anomalies, and traffic conditions. Our approach consists of Route Selection Module (RSM) and a set of routing protocols as illustrates in Fig. 1. During link failure, the self-switching route mechanism in RSM enables intermediate nodes to make effective localised decisions whether to switch RD in AODV or retransmission in NST-AODV. Once a routing decision has been made, the RSM module will wait, and evaluate the effectiveness of that decision. Based on the evaluation, it updates its response table and timeout parameter appropriately. This approach allows more effective and efficient routing strategy to be executed and reduces the number of redundant RREQs generated during transient failure.

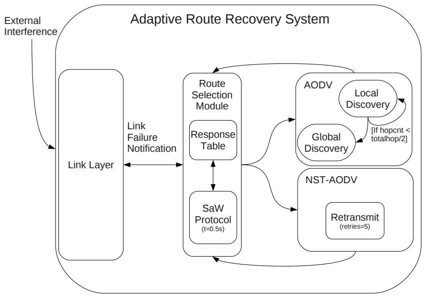

Fig. 1. The proposed MRP architecture

We modelled our MRP using a state diagram as shown in Fig. 2, highlighting different recovery states based on AODV and NST-AODV routing protocols. When a link failure notification is received, sensor nodes can either immediately send the packet, or delay its transmission depending on the current network condition and availability of next hop neighbouring node. Initially, the forwarding node waits for a short interval of 0.5s. After timeout, the node switches its routing mode to the routing algorithm with the lowest cost, in this case NST-AODV, to transmit the packet queueing in the buffer. This delays the RD, and increases the probability packet transmission as the network condition returns to normal. This wait and retransmit procedure is repeated until it reaches an initial retransmit threshold of 3 retries. Once this threshold level is reached, MRP will switch to dual mode where local repair in AODV is initiated to allow the node to determine an alternative backup route. It will further operate in a dual mode until it reaches a retransmit threshold of 5 retries, where it will switch to full AODV mode. If both local RD and retransmission are not successful, a route error packet will be send to source and the packet will be dropped. The maximum number of retransmissions and retries timeout parameters are configured based on commercially available network troubleshooting tools, such as Ping [12], where the default settings are between 3-5 for retries and 0-1 second for timeout. Based on these two parameters, each intermediate node can configure its own packet retransmission with different interval and frequency at different network conditions.

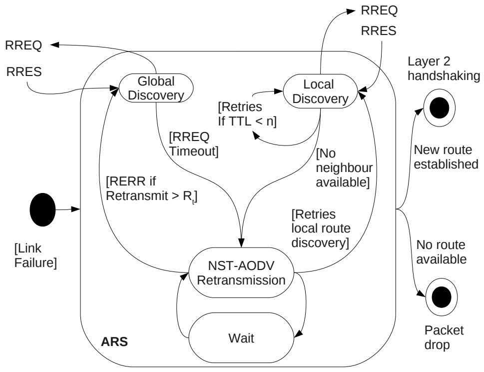

Fig. 2. Different states of MRP

IV. INVESTIGATING THE PERFORMANCE OF MRP-AODV

In this section, we investigate the impact of different transient failures in AODV, NST-AODV and MRP-AODV.

A. Experiment Setup

In our experiments, we have designed our WSNs based on 51 static nodes positioned at the top of the wall. The network is designed with redundant links that allow individual sensor node in each room to forward its packet either horizontally or vertically as shown in node 6, Fig. 3. Each source node can use three different paths to send the packets to the sink (Node 50). These paths were created during RD by intermediate nodes based on the shortest hop count to the destination. For example, if the communication between nodes 21-27-33 fail due to interference in node 27, node 21 can re-establish the route using nodes 21-20-26-32-33.

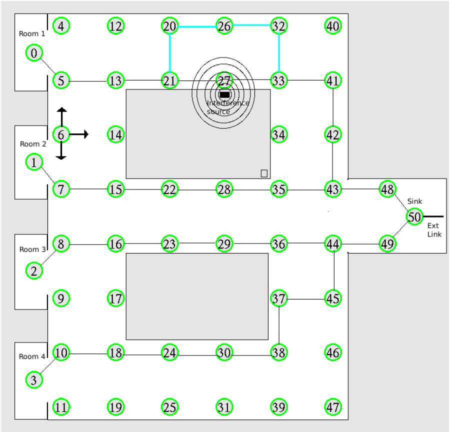

Fig. 3. Network topology based on the building

Extensive simulations were performed using Network Simulator (NS2). NS-2.34 is selected in our experiments since it has included the IEEE 802.15.4 module, developed by [13]. It is also a well established tool used by WSN's community to simulate sensor networks. However, extensions were added to support network layer retransmission in NST-AODV first, before MRP can be implemented. The parameters used in the simulation is given in Table I. The modified NS2 is available to download online[1].

TABLE I
NS SIMULATION PARAMETERS

Parameters	**Values**
Simulation area:	200x200m
Number of nodes	51 nodes
Transmission interval:	1 s
MAC:	802.15.4 (CSMA/CA)
Routing Protocol:	AODV, NST-AODV, MRP-AODV

B. Simulating the impact of transient failures

Network interference in WSNs can occur naturally due to the environment, or man-made issues such as blocking or radio jamming. Depending on the nature of the interference, it can either cause a permanent or transient failure. To investigate how these failures can affect the behaviour of the nodes, the routing protocol and the network performance, transient failures are injected to the network based on arbitrary failure patterns with varying duration and frequency.

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[1] http://www-users.cs.york.ac.uk/ thlim/sim/index.html

To simulate transient failures, an active node along the route is configured not to respond during the MAC layer two-ways handshaking for a duration of 10 seconds in 5 second interval. The effects of different numbers of transient failures are simulated and analysed in each routing protocol. Transient failures are only injected into the network after 30 seconds of each simulation run to allow the network to establish the route in normal environment. Due to the stochastic nature of the system, each experiment was repeated 35 times with different seeds to ensure the validity of experiments.

C. Evaluation metrics

To compare the performance between each routing protocol, the following performance metrics, commonly used in literature [14] were employed:

- **Average Energy Remaining:** The average energy remaining calculates the average amount of energy remain in a node. It evaluates the amount of energy required for routing.
- **Packet Delivery Rate:** Packet Delivery Rate (PDR) is the ratio of total number of data packets received to total number of data packets sent. It measures the network reliability.
- **End to End Delay:** End to end delay is the sum of the delays of each packet received over N, the total number of packets received. It compares the effectiveness and the network latency between different protocols.
- **Normalised Routing Overhead:** Routing overhead is calculated as the normalised ratio of total routing packet transmitted to the total data packet received. It measures the routing overhead generated to deliver a packet.

D. Simulation Results

To understand the impact of transient failure on each routing protocols, the traces obtained from 35 repeated runs with different seeds were evaluated. The statistics of the repeated runs for each experiment are shown using Box-and-Whisker plots, representing the medians and the inter-quartile range for each performance metrics. The horizontal axis shows the number of failure nodes.

1) Packet Delivery Rate: Figure 4a compares the packet delivery ratio between three routing algorithms: AODV, NST-AODV, and MRP-AODV. MRP-AODV is more robust to failure as the Box-and-Whisker plot in Fig. 4a has shown a smaller and more consistent distribution when we increased the number of failures. In normal condition, MRP-AODV and NST-AODV performed better than AODV as only 5% of total packet sent was lost compared to 10% in AODV. When a node was failed for 10 seconds, RREQ packets were generated by the node detecting the failure. These packets multiply and propagate through the network, creating a sudden burst of traffic that causes other nodes to drop their data packets. Differences in PDR distribution in Fig. 4a has shown that the routing switching mechanism in MRP-AODV has increased the probability of the packet delivery by 5-10%.

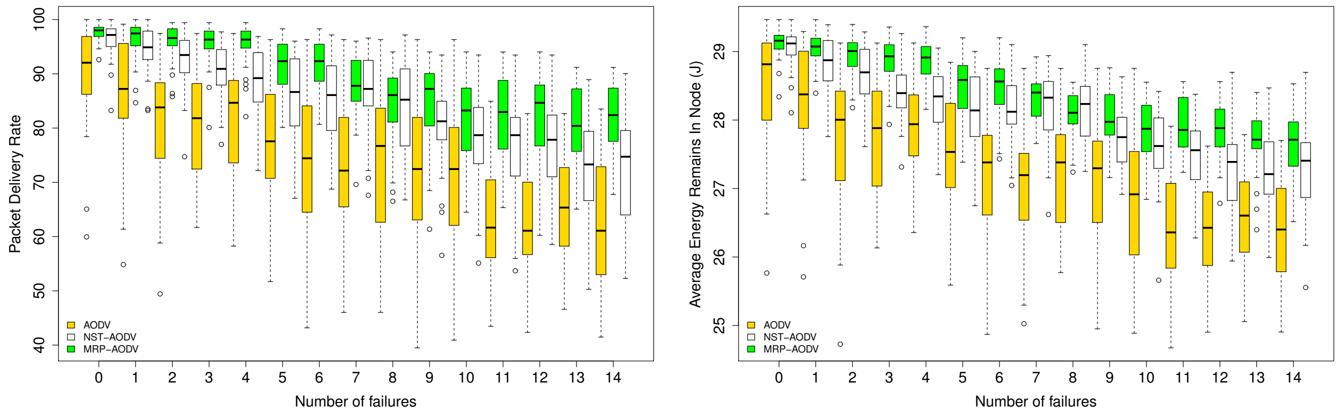
2) Average Energy: In Fig. 4b, the average amount of energy remaining in a node decreases for AODV and NST-AODV protocols compared to MRP-AODV as the number of failures increase. However, more energy is consumed in AODV and NST-AODV compared to MRP-AODV as a larger spread of distribution was observed in the average energy remaining. This is because more energy is needed to transmit the RREQs generated by RD as result of failures. The broadcast nature of AODV during RD has injected a large number of control packets, making the network more congested than normal. Although the single retransmission in NST-AODV cannot prevent RD being initiated in our failure scenario, it can handle transmission failure in a congested network caused by RD. Hence, less number of routing packets have been transmitted and higher average energy remaining is observed.

3) Routing Overhead: Fig. 4c illustrates the normalised routing overhead introduced into the network for different number of failures. In all failure conditions, MRP-AODV produces a significant lower normalised routing overhead. The use of flooding and expanding ring search in AODV have generated excessive routing packets on the networks. As we increase the number of failures, a steeper increase in routing overhead is observed in AODV as more RREQs packets are being generated. Congestion caused by excessive routing overhead in AODV has prevented the transmission of data packet resulting in more RDs. This phenomenon, known as broadcast storm, does not occur frequently in MRP-AODV as individual nodes attempt to delay RD.

4) Average Network Delay: In fig. 4d, MRP-AODV and NST-AODV have a smaller delay compared AODV when the failures are less frequent. The performance of MRP-AODV and NST-AODV begin to degrade when more than five failures are injected into the network. The retransmission in NST-AODV has not only delayed the transmission of packet, but it have also delayed the broadcast of RD as nodes attempt to content for channel. As the occurrence of failure becomes more frequent, the average time requires to deliver a packet begin to increase significantly for NST-AODV and is twice as long as AODV on average. This delay is significant lower in AODV as the data packet is send immediately once a new route is established. The performance of MRP-AODV also degrades over NST-AODV when more than five failures are injected into the network. However, one interesting characteristic observed is that it begins to saturate when more than 10 nodes are injected, and is lower and better than NST-AODV. Hence, by switching between AODV and NST-AODV, MRP-AODV has improved the overall network performance at a lower cost.

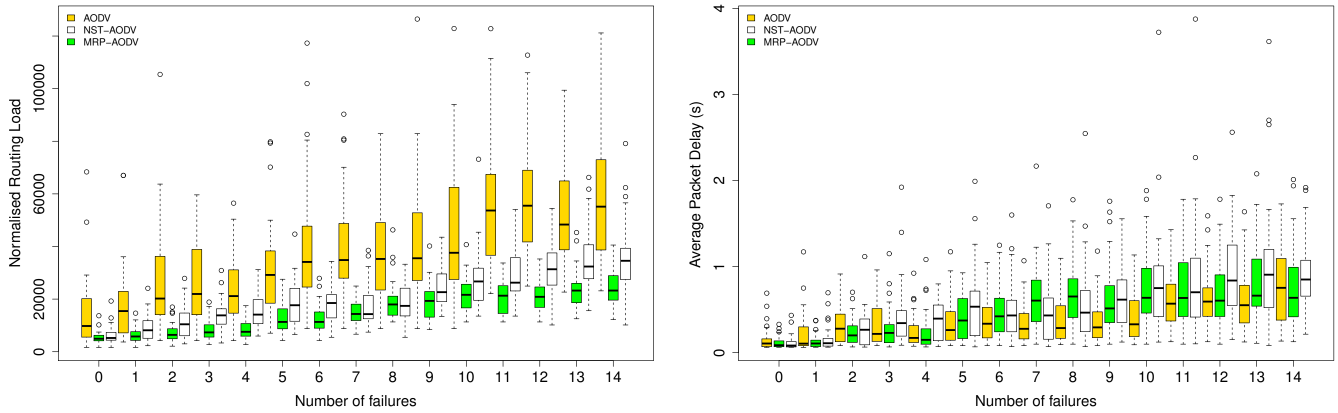
E. The Benefits of MRP

From the results, MRP-AODV has outperformed AODV and NST-AODV in term of packet delivery, average energy remaining and routing overheads. The performances of AODV have degraded very quickly as we increased the number of failures. More packets are dropped in AODV than NST-AODV



(a) Packet Deliver Rate

(b) Average Energy Remaining



(c) Routing Overhead

(d) Average Packet Delay

Fig. 4. Box-Whisker with Median and Inter-quartile range

due to network congestion created by RD packets. However, as we increased the duration and the number of failures, the packet latency in NST-AODV begins to increase. The overall performance in NST-AODV starts to degrade as it reverts to local repair in AODV. Using MRP-AODV, the distributions of packets received by the sink have shown a consistent and evenly distributed results, with a median of around 97%, when the number of failures is less than 4. The routing overhead generated in MRP-AODV is significantly lower. Hence, less energy is spent in routing. The delay observed in MRP-AODV is minimal when f_d <0.5s. However, one minor drawback of MRP-AODV is the higher packet latency obtained when we increased the failure duration, as shown in Fig. 4d and Table II, due to the additional waiting and retransmission.

V. CONCLUSION

We have performed an extensive set of simulations to test the performance and robustness of our proposed solution. Due to the limited pages, we have only presented the results for 10s failure duration with 10 number of failures. More comprehensive results can be obtained online[2]. Our experiments have demonstrated, through analysis and simulations, that a significant improvement in the number of packets delivered has been achieved. Managing the number of retransmissions in intermittent nodes has increased the probability of packets being delivered. The number of RDs are significantly lower than AODV and NST-AODV, making the networks less congested and more energy efficient. However, these performance improvements come at the expense of packet latency as each packet will spend more time in waiting and retransmission.

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[2] http://www-users.cs.york.ac.uk/ thlim/sim/index.html

TABLE II

STATISTICS FOR DIFFERENT FAILURE DURATIONS WITH FAILURE RATE OF 10 NODES

Packet delivery rate (%)												
	AODV				NST-AODV				MRP-AODV			
f_d(s)	1Qtr	Median	Mean	3Qtr	1Qtr	Median	Mean	3Qtr	1Qtr	Median	Mean	3Qtr
0.5	61.65	69.60	70.67	76.85	84.66	89.77	88.41	93.89	97.02	98.30	97.10	98.86
2	60.8	72.44	70.35	79.83	80.97	84.94	84.70	91.48	85.65	90.62	89.72	94.46
5	57.95	65.62	66.98	76.14	79.26	85.51	83.84	90.62	84.23	88.92	88.22	93.47
10	62.07	72.44	70.19	80.11	73.44	78.69	78.36	83.81	75.85	83.24	81.94	87.36
20	**59.62**	**68.75**	**67.42**	**75.00**	**61.79**	**67.61**	**66.70**	**71.73**	67.05	74.43	72.95	78.55
inf	17.76	23.30	22.12	25.99	24.86	27.56	27.84	29.69	27.13	29.55	28.92	30.82

(a) MRP-AODV is more reliability as it has the highest PDR of $97\% - 98.9\%$ when $f_d = 0.5sec$.

Average energy remaining in a node (J)												
	AODV				NST-AODV				MRP-AODV			
f_d(s)	1Qtr	Median	Mean	3Qtr	1st Q	Median	Mean	3Qtr	1st Q	Median	Mean	3Qtr
0.5	26.48	26.73	26.98	27.69	27.66	28.26	28.21	28.69	29.01	29.15	29.10	29.23
2	26.30	27.34	27.04	27.61	27.53	28.05	27.92	28.36	27.98	28.21	28.31	28.78
5	25.85	26.53	26.56	27.11	27.68	28.02	27.97	28.40	27.84	28.00	28.16	28.50
10	26.03	26.92	26.85	27.54	27.29	27.62	27.59	28.03	27.54	27.87	27.87	28.22
20	**26.34**	**26.97**	**26.85**	**27.43**	**26.97**	**27.32**	**27.36**	**27.82**	**27.31**	**27.73**	**27.70**	**28.02**
inf	26.26	26.51	26.66	26.94	25.26	25.75	25.78	26.16	25.76	26.09	26.14	26.48

(b) MRP-AODV has the lowest energy consumption rate compared to AODV and NST-AODV even when f_d=20sec.

Average packet delay (Second)												
	AODV				NST-AODV				MRP-AODV			
f_d(s)	1Qtr	Median	Mean	3Qtr	1Qtr	Median	Mean	3Qtr	1Qtr	Median	Mean	3Qtr
0.5	0.28	0.50	0.50	0.73	0.10	0.25	0.36	0.45	0.07	0.11	0.13	0.14
2	0.22	0.45	0.54	0.70	0.20	0.41	0.44	0.59	0.15	0.36	0.41	0.59
5	0.25	0.43	0.51	0.65	0.27	0.37	0.53	0.74	0.27	0.58	0.62	0.83
10	0.19	0.33	0.41	0.60	0.42	0.75	0.83	1.01	0.46	0.64	0.77	0.98
20	0.31	0.44	0.56	0.67	0.63	0.77	0.94	1.25	0.93	1.28	1.37	1.64
inf	0.14	0.31	0.50	0.73	0.10	0.25	0.37	0.39	0.10	0.18	0.29	0.32

(c) When failure duration is short (f_d=0.5sec), MRP has the lowest packet latency. As we increase f_d, the average delay in NST-AODV and MRP-AODV begins to increase when $f_d \geq 5sec$ as indicated by the dotted line.

Normalised routing overhead												
	AODV				NST-AODV				MRP-AODV			
f_d(s)	1Qtr	Median	Mean	3Qtr	1Qtr	Median	Mean	3Qtr	1Qtr	Median	Mean	3Qtr
0.5	25770	44590	42090	51950	9566	15660	16760	24240	3930	4920	5595	6477
2	26530	33580	43880	58890	14600	18860	20950	28160	8256	15540	14630	18780
5	35970	48680	52830	68650	13750	18940	20780	24740	11490	17180	16510	20710
10	27470	37600	45380	62480	19550	26710	27300	31750	16660	21620	21670	25640
20	**33850**	**39670**	**46140**	**56560**	**27480**	**33430**	**36290**	**45430**	20760	26380	26710	32900
inf	130000	161800	180200	187300	142800	169300	180300	212400	126200	145900	148200	165600

(d) MRP-AODV has the lowest routing overhead. As failure duration, f_d, increased, the routing overhead in all protocols also increase.

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