Multipath-Based Reliable Routing Protocol for Periodic Messages on Wireless Sensor Networks

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Abstract. Reliable transmission is one of the most critical requirements in industrial distributed control systems. This paper proposes a multipath-based reliable routing protocol that can guarantee a specified end-to-end target packet reception rate. In the route discovery phase, the path has highest end-to-end packet reception rate is set up and chosen to transmit data packets. To maintain the target packet reception rate, the destination node monitors periodically its actual packet reception rate and sends a feedback control message to the source if its reception rate drops below the target rate. If the source node receives the feedback message, it adds more paths while maintaining the existing paths to keep the end-to-end packet reception rate above the specified target rate. The performance of the proposed protocol has been analyzed by simulation using QualNet simulator. The simulation result has shown that the proposed protocol has a better packet reception rate than the previous routing protocols and maintains a target packet reception rate in a network where the amount of traffic changes dynamically.

Keywords: Wireless Sensor Networks; Reliable, Multipath Routing Protocol.

1 Introduction

Recently, there have been many researches on wireless sensor networks (WSNs) to be used in industrial distributed control systems. In these systems, a sensor periodically senses the physical environment and transmits the collected data to a controller, which perform a control operation based on the value received from the sensor. For stable control operation, those messages from sensors to actuators have to be transmitted reliably to the destination, and if the packet reception rate of the actuator becomes lower than a certain threshold, the performance of the control system degrades greatly [1]. However, it is difficult to provide a reliable message transmission in WSNs because higher error rate and wireless channel characteristics change dynamically over time [10]. There have been many approaches to provide reliable message transmissions on WSNs [2, 3, 5, 6], but they do not support periodic messages explicitly and do not guarantee a certain level of end-to-end packet reliability.

This paper proposes a multipath-based reliable message routing protocol for periodic messages on a WSN which guarantees a specified end-to-end target packet reception rate. For reliable message transmission for periodic traffic, the proposed

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protocol first finds a path has highest end-to-end packet reception rate and is higher than the target packet reception rate, and transmits data packets periodically through this path. To maintain the target packet reception rate, the destination node monitors periodically its actual packet reception rate and transmits a feedback control message to the source if its reception rate drops below the target value. If the source node receives the feedback message, it adds additional paths such that the sum of end-to-end packet reception rates of all the paths become greater than the target reception rate. The performance of the proposed protocol has been analyzed by simulation using QualNet simulator. The simulation result has shown that the proposed protocol has a better packet reception rate than the previous routing protocols and maintains a target packet reception rate in a network where the amount of traffic changes dynamically.

The organization of the paper is as follows. Section 2 describes related works on reliable message transmission in WSNs. Section 3 describes the protocol proposed in this paper. Section 4 describes a performance evaluation of the proposed protocol and the conclusion of the paper is described in section 5.

2 Related Works

Multipath-based reliable communication on WSNs has been paid much attention to be applied to WSNs in industrial environment [1, 7]. But, wireless links tend to be unreliable compared to wired links due to factors such as interference, attenuation, and fading, and this is more severe in wireless networks using low power like WSNs [8, 10]. Zhang et al. [9] proposed Multipath Source Routing (MSR) protocol which is a multipath-based routing algorithm based on DSR (Dynamic Source Routing). MSR inherits the advantages of DSR and uses the detection mechanism to obtain the route information and update the invalid path. In MSR, the multipaths are assumed to be completely independent when the network load is distributed, however, in route discovery phase, it cannot always find the completely independent paths. Instead, it just attempts to find the maximum node-disjoint paths, and it increases the computational complexity. Mainaud et al. [2] proposed MAODV-SIM which is based on AODV and uses multiple routes called the "emergency paths" from a source to a destination during the control message exchange. In MAODV-SIM, each link measures and maintains the Signal Intensity Metric (SIM) of the link. MAODV-SIM finds the smallest SIM value among all the links in each of the multiple paths, and chooses the path of which the smallest SIM is the highest. When the path is broken while transmitting data, another path is chosen immediately among the emergency paths, so the overhead and latency due to the link failure can be decreased efficiently. The problem of MAODV-SIM is that SIM is not a good metric to measure the reliability of the paths and the path with the smallest SIM value being the highest does not mean that the most reliable path. MP-MAODV [11] uses two node-disjoint routes to improve network efficiency and balance the network loads by distributing traffic. This approach decreases the number of route discovery and reduces routing overhead. However, because MP-MAODV protocol chooses the shortest paths for real-time communication, and so the paths are not guaranteed to be stable. K. Guan et al. [12] proposed a novel energy-efficient multipath routing protocol for WSNs. In their approach, the source and the destination broadcast RREQ packets concurrently to build trees rooted at source and destination. Multiple intermediate nodes, which belong to and are shared by the two trees, are found during this flooding. Then, each shared node transmits control packet to the source and destination to establish the route. This is a novel way to establish multipath from the source to destination. However, the drawback of this approach is that the established routes are not guaranteed to be stable and also disjoint.

3 Multipath-Based Reliable Message Routing of Periodic Messages

This section describes a multipath-based reliable message routing protocol proposed in this paper. The proposed protocol uses Packet Reception Rate (*PRR*) as the link cost metric, evaluates the end-to-end packet reception rate for each path through flooding mechanism. The proposed protocol also uses an end-to-end feedback control mechanism to maintain a specified target end-to-end *PRR*.

3.1 Reliable Message Transmission Based on End-to-End Packet Reception Rate

The PRR of a link between node x and y, $PRR(x, y)$, is defined as follows:

$$PRR(x,y) = \frac{NumberOfSuccessfulPacketTransmissionsOver(x,y)}{TotalNumerOfPacketTransmissionsOver(x,y)}$$

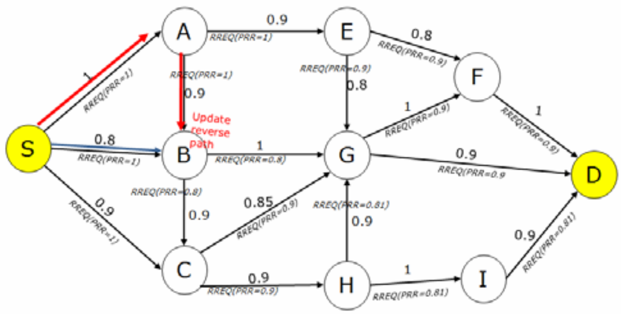
Each node in the network collects the PRR value of each link to its neighbors and periodically updates the PRR values according to the change of the traffic in the network. Given a network with PRR in the links, the end-to-end PRR of a path from a source node S to a destination node D, $e2e\_PPR(S,D)$, is defined as follows:

$$e2e\_PRR(S,D) = \prod_{(x,y)\in path(S,D)} PRR(x,y)$$

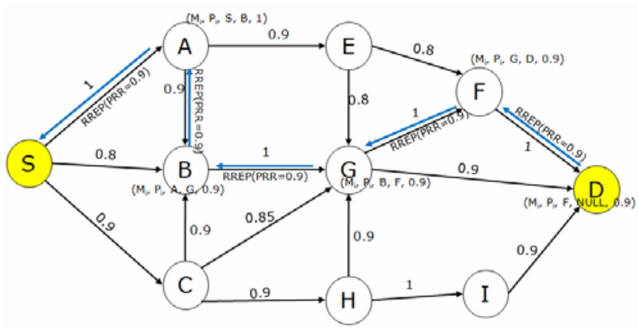
$path(S,D)$ denotes a set of successive links in the path from node S to D such as:

$$path(S,D) = \{(S, X_1), (X_1, X_2), \ldots, (X_{k-1}, X_k), (X_k, D)\}.$$

A reliable path from S to D is a path with a high *e2e_PRR* value. To find a reliable path for periodic message traffic, the source transmits a $RREQ(M_i, P_i, PRR, T\_PRR, ttl)$ packet to its destination by flooding where M_i, P_i, *PRR, T_PRR, TTL* is the periodic, period, *PRR,* required target reception rate (*T_PRR*), and time-to-live (*ttl*) fields, respectively. The *PRR* field contains the product of the PRRs of the links over which the *RREQ* packet has been transmitted. During the flooding of *RREQ* packets, when an intermediate node y receives *RREQ* packet from node x, it decreases *ttl* value by one and drops the packet if it becomes 0. Otherwise, node y updates the *PRR* value of the *RREQ* packet by multiplying $PRR(x,y)$, and searches its message queue if the message M_i is in the queue. If the message M_i does not exist in the queue, it stores the message M_i in its message queue and broadcasts *RREQ* packet. If the message M_i is in the queue, node y compares the *PRR* in the *RREQ* packet with the PRR of M_i in the message queue. If the *PRR* in the *RREQ* packet is greater than the PRR of M_i in the message queue, then node y replaces the message M_i in the message queue with the received *RREQ* packet and broadcasts the *RREQ* packet. If the *PRR* in the *RREQ* packet is smaller than or equal to the PRR of M_i in the message queue, node y drops the received *RREQ* packet. If *RREQ* packets arrive at the destination according to this flooding process, the PRR fields of the packets have the product of the PRRs of the links over which the *RREQ* packets have been transmitted. Instead of immediately transmitting RREP packet when receiving a *RREQ* packet, the destination waits for a period of time ($\Delta waitRREQ$) to collect multiple *RREQ* packets. When $\Delta waitRREQ$ is expired, the destination chooses the most reliable path by selecting the *RREQ* packet with the highest end-to-end PRR value and replying with a RREP packet.



(a) *RREQ* packet transmission process



(b) RREP packet transmission process

Fig. 1. An example of route discovery

Fig. 1(a) shows an example of route discovery by exchanging *RREQ* and *RREP* packets between a source *S* and a destination *D*. In the figure, the value on a link is the PRR value of the link. Source *S* floods *RREQ*(M_i, P_i, *PRR=1, T_PRR=0.8, ttl=10)* packet toward destination *D*. Node *A, B,* and *C* receive this *RREQ* packet first time then decrease *ttl* by one and update the *PRR* field in the packets, store the packets in their message queues and transmit *RREQ*(M_i, P_i, *1, 0.8, 9), RREQ*(M_i, P_i, *0.8, 0.8, 9)* and *RREQ*(M_i, P_i, *0.9, 0.8, 9)* packets by broadcasting, respectively. These nodes also set up the PRR values up to the source *S* in their message queues and the backward paths for forwarding RREP response packets for the *RREQ* packets. After that, if node *A* receives *RREQ*(M_i, P_i, *0.8, 0.8, 9)* packet broadcasted by node *B*, it decreases *ttl* by one and updates the PRR of the *RREQ* packet with 0.72 (=0.8*0.9), and compares it with the PRR value of message M_i maintained in its own message queue, which is 1.

Node *A* drops the *RREQ* packet because 0.72<1. On the other hand, if node *B* receives *RREQ*(M_i, P_i, *1, 0.8, 9)* packet transmitted by node *A*, it updates the PRR of the *RREQ* packet with 0.9 (=1*0.9) and compares it with the PRR value of message M_i in the message queue, which is 0.8. Node *B* broadcasts the *RREQ*(M_i, P_i, *0.9, 0.8, 8)* packet again and replaces the message M_i in the message queue with *RREQ*(M_i, P_i, *0.9, 0.8, 8)* packet because 0.9>0.8. Likewise, node *C* drops the *RREQ*(M_i, P_i, *0.8, 0.8, 9)* packet broadcasted by node *B*. In this way, if the intermediate nodes receive a *RREQ* packet which has higher PRR value than the PRR value maintained in the message queue, the nodes broadcast the *RREQ* packet again and update the PRR value and the backward path toward the source in the message queue. If the *RREQ* packets are transmitted this way, the destination node will receive *RREQ* packets through multiple paths and their PRR fields have the product of the PRRs of the links over which the *RREQ* packets have been transmitted, that is, the *e2e_PRR(S, D)*. In the example of Fig. 1, the destination node *D* can receive the following *RREQ* packets:

- Path1: $S \rightarrow A \rightarrow E) \rightarrow F \rightarrow D$: *RREQ*($M_i$, P_i, *0.72, 6)*
- Path2: $S \rightarrow A \rightarrow B \rightarrow G \rightarrow F \rightarrow D$: *RREQ*($M_i$, P_i, *0.9, 5)*
- Path3: $S \rightarrow B \rightarrow G \rightarrow D$: *RREQ*($M_i$, P_i, *0.72, 7)*
- Path4: $S \rightarrow C \rightarrow H \rightarrow I \rightarrow D$: *RREQ*($M_i$, P_i, *0.729, 6)*

Node D chooses among those *RREQ* packets, *RREQ*(M_i, P_i, *0.9, 5)* packet which has the highest *e2e_PRR* value and transmits a RREP*(PRR=0.9)* packet to the source where 0.9 is the *e2e_PRR* of the selected route. After receiving the RREP packet, the source node starts to transmit the data packets for the periodic message M_i regularly at the interval of the period P_i. While setting up the path by exchanging *RREQ* and RREP packets, each node in the path maintains an entry (M_i, P_i, BP_i, FP_i, PRR_i) for the periodic message M_i in its own message queue, where BP_i and FP_i denote a backward node and a forward node in the path and PRR_i denotes the *e2e_PRR(S, x)* between the source S and itself. Fig. 1(b) shows the transmission of RREP packet and a message queue entry maintained by each node in the established path.

3.2 Maintaining Packet Reception Rate Using Feedback Control Mechanism

During the packet transmission, the PRR value of links can be changed due to interference, links broken…etc which in turn affect the *e2e_PRR* of the established path. To reflect dynamic changing of PRR value, each node measures and updates the PRRs to its neighbors at a regular interval. The destination node maintains a target packet reception rate (*T_PRR*) for each periodic message flow, and while receiving data packets from the source, it periodically measures the actual packet reception rate (*A_PRR*) for the flow, and transmits a feedback message, *IncPRR(A_PRR) (Increase PRR)* packet which contains the current actual packet reception rate, if *A_PRR* falls down below *T_PRR*. If the source receives the *IncPRR(A_PRR)* packet, it tries to set up an additional path by transmitting *AddRREQ*(M_i, P_i, *1, N_PRR, ttl)* packet by flooding to maintain the required target packet reception rate. *N_PRR* denotes the required additional packet reception rate, which is equal to *T_PRR – A_PRR.* The *AddRREQ* packet is transmitted in the same way as the *RREQ* packet except that only the nodes which are not contained in the existing path participate in the flooding.

Fig. 2 shows the example of *IncPRR* packet transmission and *AddRREQ* packet flooding. Assumes that T*_PRR* is 0.8 (the same with example in Fig. 1) and A_PRR

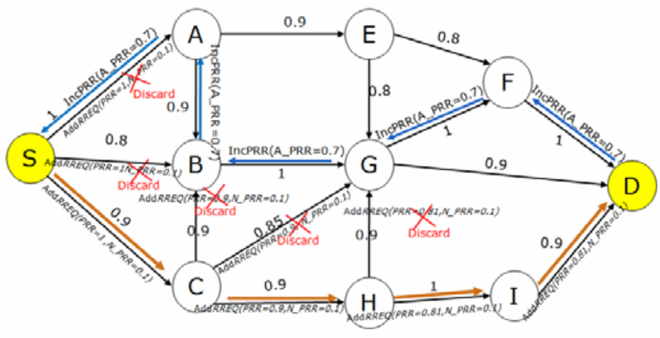


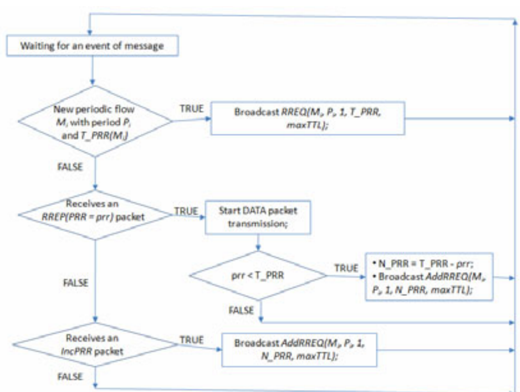
Fig. 2. Packet transmission when the actual PRR below the target value

of current flow falls down to 0.7. In this case, the destination sends *IncPRR*(*A_PRR* = 0.7) back to the source. If the source receives this packet then broadcasts *AddRREQ*(M_i, P_i, *1, N_PRR, ttl) with N_PRR* = 0.8 - 0.7 = 0.1. If the neighbors of the source *S*, *A*, *B*, and *C* receive *AddRREQ*(M_i, P_i, *1, 0.1, ttl)* packet broadcasted by S, *A* and *B* will drop the packet because they are already in the existing path between *A* and *D*. But, *C* receives the *AddRREQ*(M_i, P_i, *1, 0.1, ttl)* packet, it broadcasts the packet again and stores the packet in its message queue. In the example of Fig. 2, the *AddRREQ* packet is transmitted to the destination through the following path:

- Path1: *S*→*C*→*H*→*I*→*D*: *AddRREQ*(M_i, P_i, *0.729, 0.1, 6)*

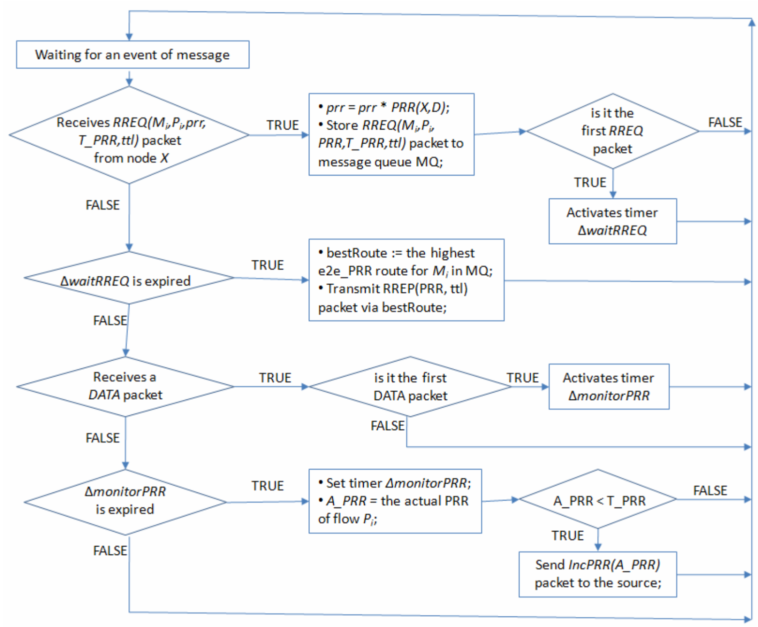
If the destination node receives multiple *AddRREQ* packets, it selects the path which has the highest *e2e_PRR* value and greater than *N_PRR* value (0.729 > 0.1), and transmits a *RREP* packet through the reverse path toward the source. The chosen path by flooding *AddRREQ* packet is a node disjoint path from the existing path, which can minimize the interference between them. If the source receives the *RREP* packet for the *AddRREQ* packet, it transmits its data packet through the two disjoint paths simultaneously, which can enhance the *e2e_PRR* for the data packets.

Fig. 3 shows the operation in each node, the source, destination, and intermediate node, for the proposed protocol.

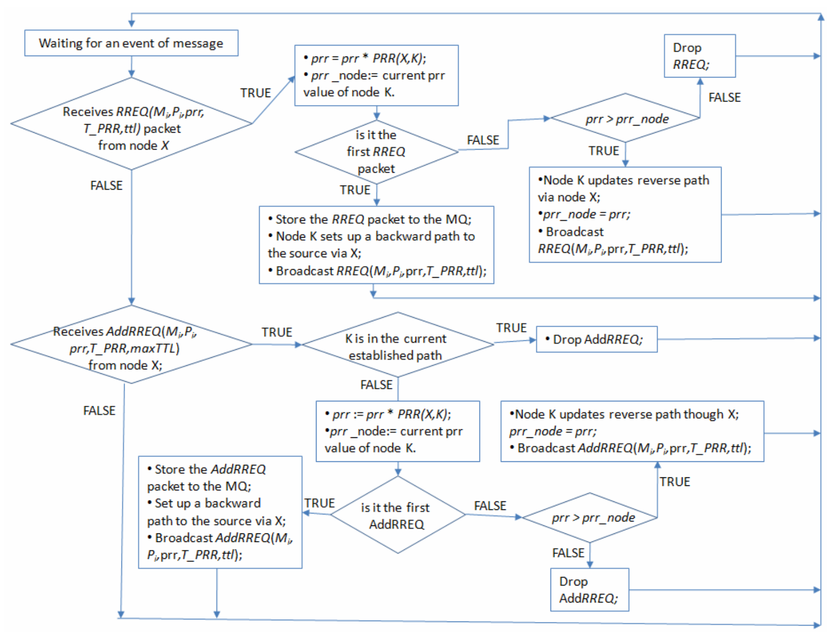


a) Source node operation (node S)

Fig. 3. The protocol operation in each node



b) Destination node operation (node D)



c) Intermediate node operation (node K)

Fig. 3. (*continued*)

4 Performance Evaluation

The performance of the proposed protocol has been evaluated through simulation using Qualnet [13]. The following table shows some parameters of our simulation:

Table 1. Simulation Parameters

Simulation time	30 minutes
Dimension	600m x 600m
Transmission range	100m
Number of data packets transmitted	500
Packet size	512 byte
Data packet interval	400ms – 2s
Waiting time for RREQs (*ΔwaitRREQ*)	250ms
PRR monitoring interval *(ΔmonitorPRR)*	10s
T_PRR	0.9
MAC protocol	802.11 DCF

In our simulation, each link in the network is assigned an initial PRR value, and after that, the PRR value of the link is monitored and updated every when a data packet is transmitted in this link. To initialize the PRR of each link, we conducted the following experiment: 108 nodes are placed at a regular distance of 5m in 4 lines topology in an area 300m x 300m. Node 1 at the central broadcasts 500 packets and the other nodes counted the number of packets successfully received. Then the average PRR value according to the Received Signal Strength (RSSI) value of the link is recorded. Base on this experiment, we initialized the PRR of a link *(x, y)* of which RSSI is *rssi* as *PRR(rssi).*

The performance of proposed protocol, AODV [4] and MAODV-SIM [2] have been evaluated in terms of the average packet reception ratio at the destination, the average end-to-end delay of packets, the average delay jitter of packets, and total number of transmitted RREQ packets by the source due to the link failure. Two scenarios have been deployed: when there is no contention (1-flow) and when the contention is very high (5-flows), the interval of each periodic flow is set to 400ms. The target e2e_PRR (*T_PRR*) value for the proposed protocol is set to 0.9. We have excuted the simulation while increasing the number of nodes in the network from 75 to 200.

Fig. 4 shows the packet delivery ratio in terms of the node density. When there is no contention (1-flow), the packet delivery ratio of the proposed protocol was almost 100% invariably as the node density increases while the AODV and the MAODV-SIM protocol decrease a little as the node density increases. In the case of 5 flows, the proposed protocol still has maintained a high average e2e_PRR compared to MAODV-SIM and AODV protocols. This result shows that the proposed protocol transmits data packet through a very reliable path. In the case of MAODV-SIM, there is a small variation of the packet delivery ratio in terms of node density due to the several weak links in the chosen path of the protocol.

Fig. 5 shows the performance result of the average end-to-end delay. In this figure, the proposed protocol shows a little larger delay than AODV and MAODV-SIM. The reason is that the proposed protocol chooses a roundabout path with a little more hops to select the most reliable path.

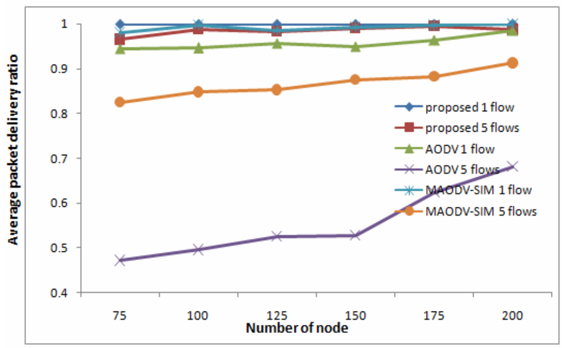


Fig. 4. Packet delivery ratio in terms of node density

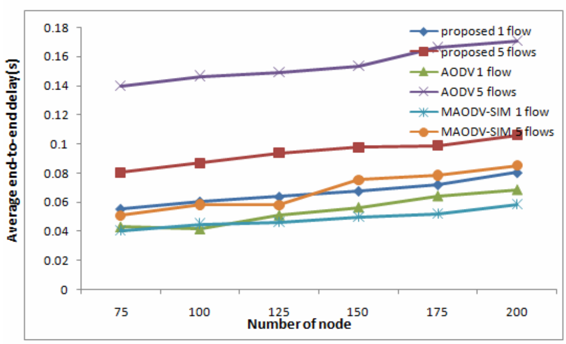


Fig. 5. End-to-end delay in terms of node density

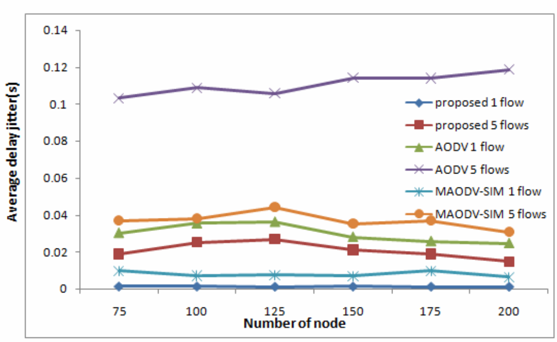


Fig. 6. Delay jitter vs. node density

Fig. 6 presents the average delay jitters of the three protocols. Contrary to the average delay, the proposed protocol showed a very little delay jitter compared with other protocols as the node density increases. In the case of 1 flow, the average delay jitter of the proposed protocol was almost 0 independent of the number of nodes in the network. In the case of 5 flows, the proposed protocol showed smaller delay jitter compared with other protocols. This result shows that the proposed protocol selects a very reliable and stable path regardless of the node density.

Fig. 7 shows the total number of transmitted RREQ packets by the source due to the link failure. As the figure shows, the proposed protocol has the smallest number of RREQ packet retransmissions. This result shows that the proposed protocol transmits data packets using more reliable and stable paths than the other protocols.

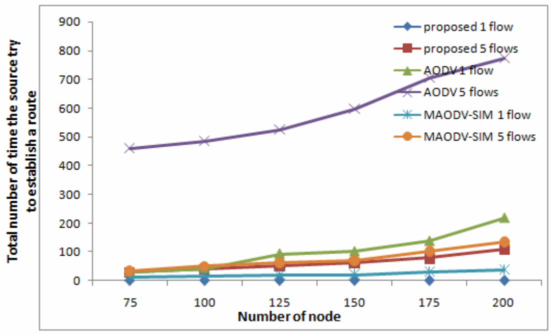


Fig. 7. Number of *RREQ* packets by the source due to link failure

The following simulation shows the capability of maintaining the target packet reception rate of the proposed protocol. After setting up the path for the first flow, we have added additional flows at the interval of 20s until the *A_PRR's* become lower than *T_PRR's* in some flows. The number of nodes in the network is 200. Fig. 8 shows the simulation result when *T_PRR* is set to 0.95 for each flow and the data packet intervals (Δt) of the flows are set to 300ms, 400ms, and 500ms depending on the flow. We can see in the figure that as flows are added more, the *A_PRR* of each flow decreases gradually. As the figure shows, the *A_PRR* of each flow recovers its target e2e_PRR after setting up additional paths using the feedback mechanism.

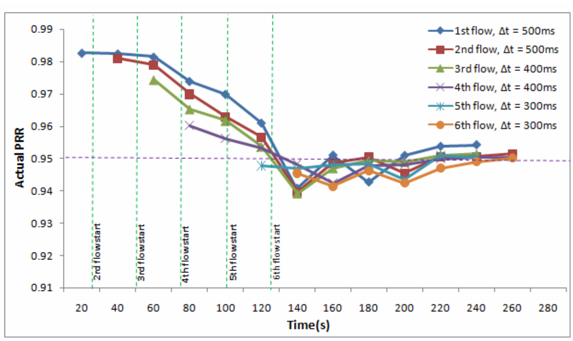


Fig. 8. An example showing the feedback mechanism: T_PRR = 0.95 and data packet interval = 300ms, 400ms, and 500ms.

5 Conclusion

In this paper, we have proposed a multipath-based reliable routing protocol for periodic messages which guarantees a certain level of packet reception rate. For reliable message transmission for periodic traffic, the path with the highest end-to-end packet reception rate is chosen to transmit data packets periodically. To maintain the target packet reception rate, the destination node monitors periodically its actual packet reception rate and transmits a feedback control message to the source if its reception rate drops below the target value. If the source node receives the feedback message, it tries to set up additional paths to the destination to use multi-paths for data transmission. The performance of the proposed protocol has been analyzed and been compared with AODV and MADDV-SIM protocols by simulation using QualNet. The simulation result has shown that the proposed protocol has a better packet reception rate than AODV and MADDV-SIM protocols and maintains a target packet reception rate in a network where the amount of traffic changes dynamically.

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