Performance of Routing Protocols in Very Large Scale Wireless Sensor Networks

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Abstract—With deployment of thousands or even tens of thousands of sensors in a wireless sensor network (WSN) feasible, the scalability of routing protocols has drawn a lot of attention. Routing protocols in ad hoc networks, such as Ad hoc On-demand Distance Vector (AODV) protocol and its enhanced versions provide one option for the routing design in a large scale WSN. Combining the strengths of AODV with link layer feedback (AODV-LLF) and AODV/Jr, an efficient routing protocol named AODV with Route Identification and RREP Capturing (AODV-RIRC) is proposed to scale up the network scope. AODV-RIRC reduces route search times and thus cut down the control overhead effectively. In our work, based on MIRAI-SF platform, simulations are implemented to prove the scalability of AODV-RIRC when applied to a large scale network with nodes up to 10000, and meanwhile to reveal the potential problems of ad hoc routing protocols when they are applied to a large scale WSN. The simulation results verify that AODV-RIRC outperforms the AODV family protocols in terms of control overhead, energy consumption, and route building time etc.

Index Terms—Large scale wireless sensor networks, Routing, AODV

I. INTRODUCTION

A wireless sensor network (WSN) is a distributed and self-organized network mainly used for target tracking in military applications, detection of catastrophic events, environment monitoring, healthcare applications etc. In such networks, every single node senses the surroundings, generates data packets while detecting specific events, and transmits them cooperatively through the network to several sink nodes. Therefore in a sense a WSN is regarded as a subclass of an ad hoc network because of the absence of infrastructure.

At present, most of the routing protocols [1-4] for WSN cannot support the large scale or even very large scale network scenarios. Because that as the network expands enormously they will introduce substantial amounts of overhead, which will degrade the network performance and shorten network lifetime. In addition, there are also many other research works in proposing routing protocols fit for large scale WSNs, including [5-7], whereas network scenario with only about 1000 nodes is created to simulate the protocol performances. The research of network performance with tens of thousands of nodes is insufficient, mainly due to the inability of simulation tools dealing with the excessive CPU and memory requirements needed for such large networks. From another point of view, since a WSN is a kind of an ad hoc network, the routing protocols designed for ad hoc networks, like Ad hoc On-demand Distance Vector (AODV) [8], Dynamic Source Routing (DSR) [9] etc, could be applicable to a WSN. However, to the best of our knowledge, the application of such ad hoc routing protocols to the WSN scenario is investigated insufficiently.

Based on these investigations, we have proposed AODV with Route Identification and RREP Capturing (AODV-RIRC) [10] for large scale WSNs combining AODV, AODV/Jr [11] and AODV-LLF [12]. And in this paper, we aim to evaluate the network performance of AODV-RIRC in the network scenarios with up to 10000 nodes, and to further reveal the potential problems of ad hoc routing protocols in such large scale networks.

In this paper we adopt MIRAI-SF [13] as simulation platform which is a scalable network simulator. It is a discrete event simulator based on Scalable Simulation Framework (SSF) [14] concept, which is scalable for a large number of network components, as well as being highly flexible. All the components in it to carry out a simulation are provided as plug-in agents. Since the plug-in agents are easily implemented and rearranged, users can perform flexible simulations. MIRAI-SF is implemented in Java language, so it can also be run on various operating systems.

The remainder of the paper is organized as follows. In Section II, a brief discussion of AODV, AODV-LLF and AODV/Jr is given, followed by Section III describes AODV-RIRC combining the strengths of the above three referenced protocols. Through simulations, Section IV evaluates the network performance of AODV-LLF, AODV/Jr, and AODV-RIRC in two scenarios. Finally Section V concludes the paper.
II. OVERVIEW OF ROUTING PROTOCOLS

A. AODV

It combines the strengths of both DSR and Destination-Sequenced Distance Vector (DSDV) [15] to build route in ad hoc networks. When a node needs to send packets to a remote destination but find no routes available, the source node broadcasts a Route Request (RREQ) message to its neighbors, and their neighbors rebroadcast the message until the message arrives at the destination node or an intermediate node which has a fresh route to the destination. The route freshness is concluded by comparing the destination sequence number in the RREQ message with that in the routing table locally. In the case that the intermediate node has a larger or equal value to the one contained in the message, it could send an RREP message to the source as a route reply. However, if there is no routing information towards the destination node in the routing tables of intermediate nodes, only the destination node can reply the RREQ packet.

During the propagation of the RREQ message, intermediate nodes cache a pointer (means a route entry in the routing table) back towards the source, and thus the RREP message could simply be sent to the upstream node, and that will be delivered to the source ultimately. During the diffusion of RREP message, each intermediate node will build a route to the destination. Upon receiving the RREP message, the source could send out all the buffered packets or collect all the RREP messages arriving in different directions, and select the optimal as the working route to deliver packets.

During the route maintenance, each node along the active route broadcasts HELLO messages for updating the real-time neighbor information, when it has not sent any broadcast message during the last HELLO_INTERVAL which is the transmission time interval of HELLO message. And if a node has not received any message from a neighbor during the last 2 * HELLO_INTERVAL period, it considers the neighbor as unreachable. Then it sends a Route Error (RERR) message to the upstream nodes to inform them of this event. And then the RERR message is delivered backwards to the source. The source node sets the route inactive and builds another one when it is desired.

B. AODV-LLF

AODV-LLF works as AODV specifies except for the route maintenance process, in which link layer feedback (LLF) is utilized to substitute HELLO mechanism. Specifically, taking IEEE 802.11 as an example, the absence of a link layer acknowledgement (ACK) frame or failure to get a Clear To Send (CTS) frame after sending a Request To Send (RTS) frame indicates loss of the link to the next hop. Then the information is passed to the network layer to modify routing table to achieve route maintenance. By this mean enormous amount of HELLO packets are saved and the delay to find the unreachable next hop is much less relative to HELLO mechanism. However, AODV-LLF works effectively in the presence of ACK and RTS/CTS scheme in link layer. Therefore it is link layer protocol dependent.

C. AODV/Jr

This protocol removes sequence numbers, gratuitous RREP, hop count, HELLO mechanism, RERR message and precursor list from AODV. Without sequence numbers and hop count, only the destination is permitted to respond the route request but not any intermediate nodes. Moreover, the destination responds the same RREQ for only once, i.e., the first received RREQ frame. In other words, other RREQ frames except the first one will be discarded by the destination, which means the fastest route is preferred. In the absence of HELLO mechanism, route maintenance is achieved by sending connect messages from end to end in an active route. For instance, data flows from the source node to the destination node, and if the destination node has not sent any packets to the source node during the last and a constant period time it will transmit a connect message to inform the source node its existence to keep the route connective. If the source node has not received any packets from the destination in the past period time, it will set the route as inactive. By this method the RERR message is saved to inform the upstream nodes about the unreachable destinations, and also the precursor list needs not to be kept any more. However, since the end-to-end delay acts as the only metric based on which a route is built, the destination is the only one permitted to respond a route request to make sure the route to be built is the least congested. Thus without any route replies from intermediate nodes, much overhead will be created to build a route. Moreover the metric of end-to-end delay may be not the best option among all the network scenarios.

III. AODV-RIRC

A. Route Building

Route building of AODV-RIRC is based on that of original AODV except that the destination ID here is always the same, which is used to specify the sink node. We call it SINK_ID in the work. When the source finds no route available to reach any sink node, it will broadcast the RREQ message to its neighbors which will also forward it via broadcast. This procedure continues until some nodes finds the SINK_ID equals to that of its own or an intermediate node finds a valid route to any one sink node cached in its routing table. Then an RREP message is created and delivered from this intermediate node or destination to the source.

Without reverse traffic from the sink nodes, we set the gratuitous flag in RREQ message as false. It means intermediate nodes do not have to send another gratuitous RREP to the destination except for the one to the source. Therefore, if all the RREP messages are responded by intermediate nodes, the reverse route, always unnecessary, will not be established for the destination. Through this operation a part of RREP messages could be reduced.
During the process of RREP delivery, the intermediate nodes not along the forwarding path may also receive the RREP messages. According to the filtering mechanism of AODV, the node first checks the receiver MAC address of the message, and will drop it if the node is not the expected receiver. Therefore we propose that since the message is received and checked and some power for receiving has been consumed, we could extract some useful route information from it. As shown in Figure 1, node E locates in the transmission range of node D. During the route replying, based on the above idea, node E captures the same RREP, and extracts the route to sink node D and caches it into its routing table. If node E has data to transmit, it can send them out immediately, meanwhile reducing propagation of some routing packets. The same process also applies to node C. After capturing the RREP message from B, node C constructs a pointer towards the destination D through node B.

Upon receiving RREP messages, either from the sink node or intermediate nodes, the source decides which one to choose as its forwarding path based on some specific metric, for instance hop count in the work. And after the route being built, all the buffered data packets are forwarded to the next hop along the route.

B. Route Maintenance

We have observed that in AODV-LLF, no more extra packets are needed to find the next hop unreachable. And it is assumed at the start of this section that the link layer feedback is available. Therefore in the work, link layer feedback is applied to substitute HELLO messages. In the implementation of the idea, after transmission of the same packet for 4 times without any ACK, it is judged the next hop is unreachable. And this event is passed to the network layer and some related entry in routing table is modified accordingly to mark the next hop unreachable.

Another point that should be pay attention to is that the nodes are not mobile and the probability of route breakage is low. We take it as a premise to lengthen the lifetime of the route or even to validate the route forever, even though it may occur that the route gets broken due to node failure for energy exhaustion. If the route has not been used for a long time, the source will not get informed of the breakage and may still deliver packets along this route which is actually invalid. To prevent data packets from being delivered along a broken route, before data forwarding, the source node will send a probe packet to the destination if the route has not been used for long. If a reply is sent back, we could use the route to forward packets, and if not, a new route finding procedure will be started up. By this method we do not have to find a new route because of timeout of the last used route which may be still connected.

IV. PERFORMANCE EVALUATION

The simulations were conducted in two scenarios, where one with network scale expansion but with nodes density approximately constant and the other pressing nodes density by adding nodes constantly to the fixed network field.

A. Network Scope Expanding

In this scenario nodes number varies from 1000 to 10000 with 1000 as interval step, and node density is kept constant and thus network area expands accordingly. There exist 16 sink nodes dispersed uniformly, and 50 sensor nodes are randomly selected as sources. Constant Bit Rate (CBR) traffic is considered for the sources, with generation rate of 3 kbps and data packets of 50 bytes in length.

Figure 3 depicts the control overhead generated during route building and route maintenance. As the figure shows AODV-RIRC generates the least overhead, which is at most 42.8% of that of AODV-LLF and 34.4% of that of
AODV/Jr respectively, and the total amount increases much more slowly because HELLO mechanism is substituted by link layer feedback which will not generate any overhead. Moreover, route capturing facilitates some potential source nodes by caching route information and reducing route search attempts. And last, route identification reserves some useful route information instead of removing them from memory space, and likewise reduces route search attempts. The performance gap between AODV-LLF and AODV/Jr is not enormous because the former abandons HELLO messages but keeps RERR and the latter eliminates RERR messages but needs connect messages from one end of the active route to the other end to maintain survival of the route. Illustrated in Figure 4 is the total energy consumption varying nodes number. It is coincident with control overhead metric due to the fact that energy spent on transmitting control overhead takes up a great majority.

Figure 3. Control overhead versus nodes number

Figure 4. Energy consumption versus nodes number

Figure 5 demonstrates the averaged route building time of the four routing protocols. It is shown that the time for route building of AODV-RIRC is 47.5% and 37% of that of AODV-LLF and AODV/Jr averagely. Wherein AODV-RIRC outperforms the other two schemes because parts of sources do not have to initiate route searches for that they have captured route information during RREP delivery to the other sources. Additionally even invalid for being unused for a long time, the route could also be checked whether connected or not by sending a probe packet instead of initiating a new route searching process. Thus the averaged time for building route declines. Meanwhile it can be seen from the figure that AODV/Jr needs longer time to build a route. This can be explained by the fact that only destinations are allowed to respond a route request. However in AODV-LLF, intermediate nodes that have a fresh route to the destination could also reply an RREP packet to the source. By this means the time needed to build a route is shorter in AODV-LLF than that in AODV/Jr.

B. Node Desity Being Increased

In this subsection another scenario is considered with a fixed network area but nodes density being pressed as nodes number increases. Simulations are implemented varying nodes number from 2000 to 10000 with interval step of 2000. Each simulation runs for 300 seconds, and other network configurations stay the same with that in Section IV.1. Apart from simulations with 50 sources, simulations with 70 sources are also implemented to observe network performances with more traffic sources.

The superiority of AODV-RIRC over the others in scaling up with network expansion is reflected in terms of overhead reduction which is shown in Figure 6. AODV-RIRC outperforms the others in controlling overhead growth. As shown in Figure 6, the total amount of overhead of AODV-LLF and AODV/Jr approximately increases linearly, whereas that of AODV-RIRC increases more smoothly. It can be observed AODV-RIRC could reduce control overhead at most by 77.9% and 83.7%
relative to AODV-LLF when the source number is 50 and 70 respectively. And relative to AODV/Jr it could reduce overhead at most by 77.9% and 83.4% respectively with sources of 50 and 70. Another should be noted that the addition of traffic sources in AODV-LLF and AODV/Jr contributes to another part of overhead, whereas there is subtle difference for AODV-RIRC in such a scenario. For instance, when the sources rise from 50 to 70, the control overhead averagely increases by 31.8% for AODV-LLF and by 31.1% for AODV/Jr. Moreover it increases only by 15.3% for AODV-RIRC. The major contribution of that is the RREP capturing that reduces the total route building times and thus the control overhead especially after 4000 nodes. Thus in the dense networks, because of RREP capturing the total route building times and the control overhead resulted are reduced. Apart from RREP capturing, route identification also play a part in reducing control overhead. The routes in AODV-LLF and AODV/Jr will expire after some period time and they have to be rebuilt when desired. However, in AODV-RIRC the routes just needs being checked whether connected or not instead of rebuilding them before they are used.

The energy consumption of all the sensors is illustrated in Figure 7. The trend of all the curves is similar to that of Figure 6 because the energy depleted in control overhead takes up a big part. Therefore the reason in Figure 6 could also be applied to interpret the differences in this figure. With 50 source nodes, AODV-RIRC could save energy consumption by at most 61.2% and 61% relative to AODV-LLF and AODV/Jr respectively, and with 70 source nodes it could save energy consumption by at most 64% and 63.4% relative to AODV-LLF and AODV/Jr. Especially when the source nodes rise from 50 to 70, AODV-LLF needs 37.9% more energy and AODV/Jr needs 35.7% more energy to operate, whereas AODV-RIRC needs 26.7% more energy to run successfully. Combining the results in Figure 3 and Figure 4, it could be concluded that AODV-RIRC is more efficient in scaling up with nodes density increase in reducing overhead and energy consumption.

In Figure 8 the averaged route building time of referenced protocols is pictured. The route building time for AODV-RIRC is lower than that of other two, about 65.7% and 59.5% averagely less than AODV-LLF and AODV/Jr with 50 sources, and about 72% and 63.2% less than AODV-LLF and AODV/Jr with 70 sources. It is owing to RREP capturing and route identification of AODV-RIRC. The former contributes to the reduction of route search times and the latter helps avoid route rebuilding, and then the averaged route building time for AODV-RIRC is brought down accordingly. It can be observed in the curves that the route building time decreases with network becoming much denser. It is because in the more sparse networks the routes are built respectively. However, as the network becomes denser, the RREQ packets are propagated along much more different paths to the destination, and correspondingly much more RREP packets are delivered to the source. Then a number of intermediate nodes construct the paths towards the sink. Although the routes built by the
intermediated nodes will get stale after some interval, they provide a favorable condition to reduce the averaged route building time generally. Therefore the averaged route building time decreases as the nodes number grows. The last point worth being noted in Figure 8 is that route building time for AODV/Jr is shorter than that for AODV-LLF, which is contrary to the results in Figure 5. In Figure 5, the intermediate nodes of AODV-LLF could respond RREQ because the route information in their memory space is still valid due to the shorter simulation duration of 30s. However in this scenario the simulation time is stretched to 300 seconds which is much longer than that in Section IV, and as a result the intermediate nodes can not reply RREP packets any more for the route information being invalid. Moreover, AODV/Jr intends to find the fastest route, and therefore the route building time of AODV/Jr is shorter than that of AODV-LLF. But in the final analysis, AODV-RIRC outperforms other protocols in the aspect of reducing the route building time whatever the scenario changes.

C. Potential Problems of Ad hoc Routing Protocols when Applied to WSN

Via simulations presented above, it is proved AODV-RIRC is more scalable than the other three referenced protocols when applied to a very large scale WSN. And there are three main obstacles limiting the application of ad hoc routing protocols in a WSN.

First, the stationary network scenario of WSN is not taken as an advantage in route maintenance, and the refresh of routing table is not necessary. The refresh of routing table of ad hoc routing protocols is required to make the transmitter realize the route has been invalid and thus avoid dropping out packets. However, without movement in WSN, the refresh of routing table brings no benefits but route expiration and route rebuilding and much overhead accordingly. Under these circumstances, the route maintenance in a reactive manner should be considered. That means the entry in the routing table is kept valid until some next hop is detected unreachable explicitly.

Second, during route building, control packets are flooded blindly and redundantly especially in the case of dense deployment of sensor devices, making the network loaded heavily. Flooding RREQ packets across the network is aimed at finding the destination without any knowledge of the location of the destination. But the difference of network scenario between mobile ad hoc networks and WSN is that there are just limited several destinations, sink nodes specifically here, and no movements in WSN. If the source recognizes the position of sink nodes approximately, the RREQ packets can be flooded directionally. Moreover, in ad hoc routing protocols, every intermediate node forwards the RREQ packets, which leads to the redundant flooding and especially in a dense network results in a more congested network. Thus in the case of dense networks, clustering the network is a better choice. By this means, only part of sensor nodes are allowed to forward RREQ packets.

And last, the one-to-one communication in ad hoc networks is inappropriate for WSNs. With ad hoc routing protocols, whenever having packets to send a sensor builds a route independently. However, in WSN many source nodes may have the same destination to transmit data packets to. Although there is no fault to build routes independently, enormous overhead will be created if there are too many source nodes. A better option is that a forwarding path to the common destination can be cached during one route search by as many source nodes as possible.

V. CONCLUSIONS

In the paper, the network performance of AODV-RIRC is evaluated in the network scenarios with up to 10000 nodes in two scenarios. Via simulations AODV-RIRC outperforms other two protocols in metrics of control overhead, energy consumption, and averaged route building time. For instance, in the simulation of scenario with nodes density fixed, the overhead of AODV-RIRC is at most 42.8% and 34.4% of AODV-LLF and AODV/Jr respectively. And in another simulation scenario with nodes density being pressed, AODV-RIRC can reduce control overhead at most by 77.9% and 83.7% relative to AODV-LLF when there are 50 source nodes and 70 source nodes respectively. And the similar results of AODV-RIRC relative to AODV/Jr can also be observed. Moreover, the major obstacles blocking the application of ad hoc routing protocols in large scale WSNs were revealed at the end of the paper, which presented heuristic ideas for the routing design in very large scale WSNs.

ACKNOWLEDGMENT

This work was supported by National Science and Technology Major Project (2011ZX03001-007-01), NSFC for Distinguished Young Scholars (60725105), NSFC Project (60702057), SRF for ROCS, SEM, the Fundamental Research Funds for the Central Universities (JY10000901002), Special Research Fund of State Key Laboratory (ISN1102003), Open Research Fund of National Mobile Communications Research Laboratory, Southeast University and the 111 Project (B08038).

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