Route-over vs Mesh-under Routing in 6LoWPAN

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ABSTRACT

Transmission of IPv6 packets over Low-power Wireless Personal Area Networks (6LoWPAN) was considered nearly impractical once. The size of IPv6 packets is much larger than the packet size of the IEEE 802.15.4 data link layer. 6LoWPAN implements an adaptation layer between network and data link layers. Main purpose of the adaptation layer is to fragment and reassemble IPv6 packets. Implementation of the adaptation layer enhances the routing/forwarding decision of packets both network and adaptation layers. We can divide the routing scheme in 6LoWPAN into two categories: the mesh-under and the route-over, based on the routing decision taken on adaptation layer or network layer respectively. In this paper we perform an analytical comparison between these two schemes in terms of the packet/fragment arrival probability, the total number of transmissions and the total delay between source and destination. We also compare the selective fragment retransmission mechanism between mesh-under and route-over schemes.

Categories and Subject Descriptors

H.4 [**Wireless LANs and Wireless PANs**]: Route-over and Mesh-under Routing

General Terms

Measurement and Performance

Keywords

6LoWPAN, routing, WSN

1. INTRODUCTION

IEEE 802.15.4 standard defines a wireless link for low-power wireless personal area networks (LoWPAN) which is extensively applied in embedded applications like habitat monitoring, building automation, security, object tracking, nuclear reactor control, fire detection and traffic monitoring. It is also used in several human-centered applications like health monitoring, device interconnection, and fitness related applications. Implementation of these applications over a large area requires huge number of low-power and low-cost nodes/devices. It is also deemed that these application should have a prolong life cycle.

IEEE 802.15.4 networking devices have limited capabilities as compared to other WPAN or WLAN. Key characteristics of IEEE 802.15.4 are the small MTU size of 127 bytes, low data rate of 250kbps if it operates in 2.4 GHz band, short range communication and the built-in AES-128 encryption and authentication method. In addition to the long address (64-bit EUID), it also supports the 16-bit short-address for a device. Hence, these short-addresses reduce the communication overhead and maintain distinctive communication within a WPAN. A typical RAM size of LoWPAN devices ranges from 2KB to 10KB. IPv6 [4] is an Internet layer protocol and the successor of IPv4. IPv6 solves the IP address space from 32 bits to 128 bits and the minimum MTU of IPv6 is 1,280 bytes. The transmission of IPv6 packets over LoWPAN is difficult because of thinking that IP is resource-intensive and the MTU of IPv6 is 1,280 bytes whereas the MTU of the IEEE 802.15.4 data link layer is 127 bytes.

6LoWPAN is defined by IETF standard and described in RFC 4919 [5]. 6LoWPAN implements an adaptation layer between network and data link layers to support transmission of IPv6 packets over LoWPAN. After the implementation of the adaptation layer it is possible to take routing/forwarding decisions either in the traditional network layer or the adaptation layer. If the routing decision is taken in the network layer we call it route-over and if the decision is taken in the adaptation layer we call it mesh-under.

The contribution of this paper is the analysis of the mesh-under and the route-over routing schemes in 6LoWPAN. We show that how these two schemes differ in terms of the fragment/packet arrival probability, retransmission policies, the total delay between source and destination (based on number of fragments in a packet), and the number of hops between source and destination. The rest of the paper is described as follows: Section 2 describes the background of 6LoWPAN. Section 3 describes the mesh-under and the route-over routing schemes. Section 4 performs a mathematical comparison between these two schemes. Section 5 discusses about our observations and finally section 6 concludes the paper.

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2. BACKGROUND

The IETF standard [5] defines the overview, assumptions, problem statement and goals for 6LoWPANs. The packet size of IPv6 is much larger than the MTU of IEEE 802.15.4 data link layer which leads to the fragmentation and compression of IPv6 packets. Energy efficiency is also an important issue for the transmission of 6LoWPANs. 6LoWPAN is an IETF standard about how to transit IPv6 packets over LoWPANs which is described in RFC 4944 [2]. 6LoWPAN introduces an adaptation layer between data link and network layers in TCP/IP protocol stacks. It dramatically reduces IP transmission overhead by using header compression and fragments IPv6 packets to support minimum MTU of IPv6 packets. 6LoWPAN also employs the mesh forwarding in data-link layer to deliver an IPv6 packet from source to destination over a multihop scenario. One byte dispatch value of adaptation layer is employed to determine whether the frame is a LoWPAN frame or not. If the frame is a LoWPAN frame then type specific headers are taken place as part of dispatch value. For the specific value of the type specific header there may exist uncompressed/compressed IPv6 header, fragmentation header, mesh header or broadcast header. If the size of the IP packet is bigger than the MTU of the data link layer then fragmentation is essential. The fragmentation header is taken place after the dispatch value of the adaptation layer. The appearance of the fragmentation header is determined by a specific value of the dispatch byte. The dispatch value for the first fragment and subsequent fragments are different due to the simplicity of the fragmentation. The offset of the fragment can only express multiples of eight bytes length. So except the final fragment, all other fragments are multiples of eight bytes. If there are more than one header in the same packet, then the mesh addressing header, the broadcast header and the fragmentation header are placed sequentially.

Issues of route-over vs mesh-under routing are mentioned by [1]. The 6LoWPAN architecture [11] addresses many issues of route-over and mesh-under routing schemes of 6LoWPAN. The IETF 6LoWPAN working group is also working to define the problem statement and requirements for 6LoWPAN routing [3]. Related works [1] and [11] only discuss about some issues of route-over and mesh-under routing schemes. However, they do not provide any analytical comparisons between route-over and mesh-under schemes.

3. ROUTING IN 6LOWPAN

The routing protocol in 6LoWPAN is sensitive because capabilities of nodes are limited in terms of energy, transmission range etc. There have been numerous developments of routing protocols for LoWPAN ([7]∼ [10]). Based on application scenarios, the routing in 6LoWPAN can be classified as: flooding, data-aware routing, geographic routing, probabilistic routing, event-driven, query-based routing and hierarchical routing.

Based on which layer the routing decision i.e. the datagram forwarding occurs we can divide routing protocols in 6LoWPAN into two categories: the mesh-under and the route-over. Fig. 1 shows layers on which the routing decision occurs in TCP/IP protocol stack for 6LoWPAN. For mesh-under scheme the routing decision is taken in adaptation layer, whereas for route-over scheme the decision is taken in network layer. Routing issues in route-over and mesh-under

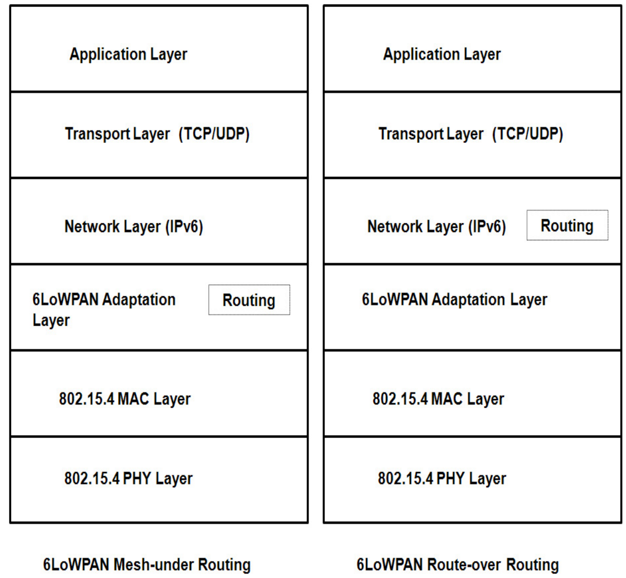

Figure 1: Routing decision layer

schemes mainly differs in packet/fragment forwarding process rather than route establishment phase. Following subsections describe the mesh-under and the route-over routing schemes in details.

3.1 Mesh-under

In mesh-under scheme, the network layer does not perform any IP routing inside a LoWPAN. The adaptation layer performs the mesh routing and forwards packets to the destination over multiple radio hops. In mesh-under scheme, routing and forwarding are performed at link layer based on 802.15.4 frame or the 6LoWPAN header. To send a packet to a particular destination, the EUI 64 bit address or the 16 bit short address is used and sent it to a neighbor node to move the packet closer to the destination. Multiple link layer hops are used to complete a single IP hop and so it is called mesh-under. 6LoWPAN employs the idea of the originator and the final address to describe the original source and the ultimate destination node of a single IP hop within a PAN respectively. As the link layer originator and the final destination address are included within the 6LoWPAN header, the mesh delivery for any protocol on the adaptation layer is possible. An IP packet is fragmented by the adaptation layer to a number of fragments. These fragments are delivered to the next hop by mesh routing and eventually reach to the destination. Different fragments of an IP packet can go through different paths and they are gathered at the destination. If all fragments are reached successfully, then the adaptation layer of the destination node reassembles all fragments and creates an IP packet. In case of any fragment missing in the forwarding process the entire IP packet i.e. all fragments for this IP packet are retransmitted to the destination for recovery.

3.2 Route-over

In route-over scheme all routing decisions are taken in the network layer where each node acts as an IP router. In route-over, each link layer hop is an IP hop. The IP routing supports the forwarding of packets between these links. In the forwarding process IP routing tables and IPv6 hop-by-hop options are used. For routing and forwarding processes the network layer takes decision using the additional encapsulated IP header. The adaptation layer of 6LoWPAN establishes a direct mapping between the frame and the IP headers. When an IP packet is fragmented by the adaptation layer, fragments are sent to the next hop based on the routing table information. The adaptation layer of the next hop checks received fragments. If all fragments are received successfully, the adaptation layer creates an IP packet from fragments and send it to the network layer. If the packet is destined for itself, the network layer sends the IP packet to the transport layer, otherwise forwards the packet to the next hop based on the routing table information. If there are one or more fragments missing, then all fragments are retransmitted to one hop distance. After receiving all fragments successfully the adaptation layer creates an IP packet from these fragments and pass it to the network layer. The network layer then forwards or processes the IP packet based on the destination of the packet and the routing table information.

3.3 Selective Retransmission for Mesh-under

Generally in mesh-under scheme all fragments are retransmitted from the source to the destination if one or more fragments are lost in the routing path. We can use a selective fragment retransmission mechanism based on a selective negative acknowledgement (NACK) from the destination to the source. According to the NACK only lost fragments are retransmitted and previously sent fragments are saved in the buffer of the destination. Then the adaptation layer of the destination create an IP packet from saved and newly received fragments. We call it "Selective Retransmission for Mesh-under (SRMU)" in this paper.

3.4 Selective Retransmission for Route-over

Generally in route-over scheme all fragments are retransmitted to the next hop if one or more fragments are lost in the path. If one or more fragments are lost between a sender and a receiver in one hop distance a selective NACK can be acknowledged to the sender for retransmission of lost fragments. We can save all fragments at the buffer of the next hop. After receiving lost fragments successfully, the adaptation layer (re)assemble saved and newly received fragments to an IP-packet. We named the whole process as "Selective Retransmission for Route-over (SRRO)" in this paper.

4. ANALYSIS

In this section we find out probabilistic model for route-over and mesh-under schemes. Let assume that a received IP packet from the network layer is divided into f fragments by the adaptation layer. Also, assume that h be the number of hops traveled by each fragment from source to destination.

4.1 Energy Efficiency in No Recovery Case

In the case of route-over, the lose of any fragment at any intermediate hop results in the jettison of all subsequent received fragments. While in the case of mesh-under, if any fragment is lost at intermediate hops, then the rest fragments will be propagated to the destination because each fragment is treated independently in the entire network except the destination node. Hence, the route-over recovery scheme is energy efficient than that of mesh-under because it does not send any unnecessary fragment to next hops.

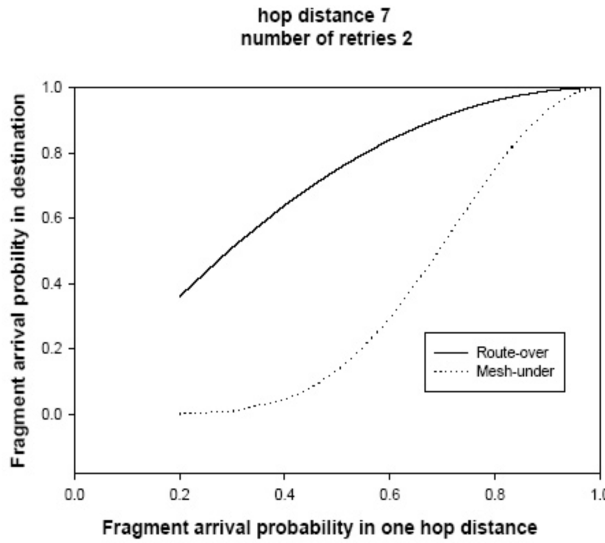

Figure 2: Fragment arrival probabilities in the destination for the probability of success in one hop distance.

4.2 Probability of Arrival of a Fragment

Let p be the probability of successful arrival of a fragment in one hop distance in a single attempt. N is the number of retries to send a fragment to the next hop. So, after N retries the probability of reaching a fragment, P_{ro}, to one hop distance is given by Eq. 1.

$$P_{ro} = \sum_{i=1}^{N} p(1-p)^{i-1} \tag{1}$$

In route-over scheme, lost fragments are recovered at hop-by-hop basis. So, for h hop distance, the probability of reaching to multihop distance is same because each time all fragments are reassembled, fragmented and transmitted with same probability to next hop which is given in Eq. 1.

As lost fragments are checked end-to-end for mesh-under scheme, then for a specific number of retries N and for h hop distance the probability, P_{mu} Eq. 2 of arrival for a fragment.

$$P_{mu} = (\sum_{i=1}^{N} p(1-p)^{i-1})^h \tag{2}$$

Fig. 2 shows fragment arrival probabilities in the destination of a fragment for the probability in one hop distance with number of retries 2 and number of hops 7. We observe that for route-over case, the probability of reaching a fragment is higher than that of mesh-under. The reason is that, at each hop the IP packet is regenerated and then sent again with initial probability. However, for mesh-under case, no creation of IP packet is done at intermediate node and each fragment goes to the destination individually. So, the probability decreases after traveling each hop gradually.

4.3 Total Transmission of Packets

In this section we assume that the shortest routing path is characterized by the successful arrival of messages at intermediate nodes between the source and the destination. By supposing this we want to determine the expected number of messages successful delivered or arrived messages, starting at i^{th} - intermediate node, make before reaching either source or destination i.e 0, n, respectively. Here we would call this quantity m_i, $i = 1, ..., n-1$. The probability of j^{th}, $j \geq 1$, successful arrival of message at any intermediate node. We want to find out the expected number of intermediate nodes/hops required for communication with final destination. Let B, Eq. 3, be the minimum number of intermediate nodes between source and destination.

$$B = Min\{m : \{\sum_{j=1}^{m} X_j = -i \bigvee \sum_{j=1}^{j} X_j = n-i\}\} \tag{3}$$

Every intermediate hop is deemed to successfully receive and transmit the packet to the next hop or final destination. The total expected number of successful transmission in route-over Eq. 4.

$$E[\sum_{j=1}^{B} X_j] = (2p-1)E[B] \tag{4}$$

The total expected number of successful transmission in mesh-under Eq. 5.

$$E[\sum_{j=1}^{B} X_j] = pE[B] - q \tag{5}$$

Here $E[B]$, Eq. 7, denotes the expected number of fastest ferry and $E[\sum_{j=1}^{B} X_j]$ represents the expected number of successful transmission from the source to the destination. The successful routed packets i.e.,(Eq. 5), depends upon the geometric probabilistic distribution at each hop.

$$\sum_{j=1}^{B} X_j = \begin{cases} n-i, & with\ prob.\ \alpha \\ -i, & with\ prob.\ 1-\alpha \end{cases} \tag{6}$$

$$(2p-1)E[B] = \alpha - i \tag{7}$$

$$E[B] = \frac{1}{2p-1}\left(\frac{n[1-(q/p)^i]}{1-(q/p)^n} - i\right) \tag{8}$$

p is the success probability of receiving and forwarding the packet/fragment while $q = 1 - p$ is the failure probability at each hop.

4.4 Total Delay Between Source and Destination

Let T_w is the waiting time in a contention period. T_p is the propagation delay of a fragment and T_{np} is the node processing time of a fragment. Let h is the number of hops to be traveled and f is the number of fragments. The total end-to-end transmission delay for mesh-under routing scheme, T_{tmu}, is:

$$T_{tmu} = (T_w + T_p)h + T_{np}(h-1) + (f-1)(T_w + T_p) \tag{9}$$

In Eq. 9, $(T_w + T_p)h$ is the sum of the total waiting time in a contention period and the total propagation delay, $T_{np}(h-1)$ is the total node processing time, and $(f-1)(T_w + T_p)$ is the total waiting time for all fragments except the first one for all nodes in the route.

The total transmission delay for route-over routing scheme, T_{tro} is:

$$T_{tro} = (T_w + T_p)f * h + (h-1) * (T_{np} + \delta) \tag{10}$$

In Eq.10, δ is the time for reassembly and fragmentation at intermediate hops. Here, $(T_w + T_p)f * h$ is the waiting time a contention period and propagation delay for f fragments and h hops. $(h-1) * (T_{np})$ is the time for intermediate node processing and reassembly. The route-over scheme includes the delay of reassembly of fragments and fragmentation of IP packets at intermediate nodes. So, in case of the total delay between the source and the destination the mesh-under scheme performs better than the route-over scheme.

4.5 Buffer Size

Sensor nodes have limited buffer size. Route-over and SRRO recovery mechanisms store all fragments and wait for other fragments. If the network has too many traffics and one node is receiving packets from different nodes (as an intermediate hop) then there is a chance of buffer overflow. On the other hand in mesh-under or SRMU, as there is no hop-by-hop recovery, so the buffer size of intermediate nodes does not take effect if the network has too many traffic.

4.6 End-to-End vs Hop-by-Hop Recovery for SRRO and SRMU

Recoveries of mesh-under and route-over can be considered as end-to-end and hop-by-hop respectively. In traditional mesh-under or route-over scheme when an IP packet is sent to the destination or to the next hop and if fragmentation occurs due to the IP packet size, then there must have reassembly of fragments at the next hop or at the destination based on schemes.

For the case of SRMU, if an IP packet is fragmented into F fragments and transmitted across H hops to the destination, then the expected number of fragments reachable at the destination is given in Eq. 11.

$$E[f(F,H)] = \sum_{m=1}^{F} m.P_{mu}^{m}(1-P_{mu})^{F-m} \tag{11}$$

where P_{mu} is the mesh-under end-to-end probability from Eq. 2. If we transmit a fragment across H hops, the expected number of hops, $E[f_h(H)]$, through which the fragment will pass is given in Eq. 12.

$$E[f_h(H)] = \sum_{m=1}^{H-1} m.P_{mu}^{m-1}(1-P_{mu}) \tag{12}$$

The approximate cost, C_{apx}, for sending F fragments in one attempt is

$$C_{apx} = H.E[f(F,H)] + E[f_h(H)].(F - E[f(F,H)]) \tag{13}$$

In SRMU case if some fragments are lost while first attempt we send a selective NACK and retransmit lost fragments only. So, at second attempt we can get how many fragments have been lost and retransmit them and get the transmission count using Eq. 11 $\sim$ 13. We can recursively calculate number of transmissions for subsequent steps for the case of fragment transmission failures in k^{th} attempt. If we add all these transmission counts we can get total number of fragment transmissions for the SRMU mechanism.

For the case of SRRO, the recovery is done in hop-by-hop basis. So, an IP packet will go to the next hop and the next hop will buffer fragments and check whether all fragments have been reached or not. If there is any fragment transmission failure we send a selective NACK to retransmit only lost fragments. So, when all fragments are reached at the next hop (or at the destination) the 6LoWPAN adaptation layer will reassemble all fragments and create an IP packet. Thus the IP packet will traverse from the source to the destination. For the SRRO case the expected number of retries to move a fragment in one hop successfully is

$$E[r(N)] = \sum_{k=1}^{\infty} k.P_{ro}(1-P_{ro})^{k-1} \tag{14}$$

where P_{ro} is the route-over probability from Eq. 1. So, for H hops if the number of fragments from the IP packet is F then the total number of transmissions is

$$E[f(H,F)] = F.H.E[r(N)] \tag{15}$$

If we count total number of transmissions to send an IP packet over H hop distance then we observe that from Eq. 11 $\sim$ 15 SRRO requires less number of transmissions than SRMU. The difference increases rapidly if the number of hops or the number of fragments from the IP packet increases. RMST [6] also showed us a similar kind of analysis of hop-by-hop vs end-to-end segment recovery for transport layer. They also showed that hop-by-hop performs better than end-to-end recovery scheme. It is clear from the analysis that if we implement selective NACK and retransmit only lost fragments, then it will reduce the total number of retransmissions than that of traditional recovery of mesh-under or route-over scheme.

5. OBSERVATIONS

From the probability analysis of both route-over and mesh-under schemes we can say that route-over is efficient than mesh-under for the case of fragment arrival ratio in the destination. Route-over and mesh-under schemes both retransmit all fragments if one or more fragment failure occurs which creates overhead in the network. Selective fragment recovery mechanisms (SRRO or SRMU) may overcome this problem. We know that the buffer size of sensor nodes is limited, so if the amount of traffic generated in the network is too high and one node is used as intermediate node of several transmission paths, then there is a possibility of buffer overflow in route-over. However, in mesh-under scheme there is no possibility of buffer overflow at intermediate nodes. In case of the total delay mesh-under scheme is better than route-over scheme. Route-over scheme is good for the environment where there is more chance to lose fragments in the path, because of its hop-by-hop recovery mechanism. On the other hand, mesh-under scheme does not have any overhead of reassembly and fragmentation at intermediate nodes but if the size of the IP packet is very big or the number of hops in the routing path is big, then it has higher probability to lose fragments while routing. So, for small IP packet size or less number of hops mesh-under scheme may perform better than route-over scheme. Mesh-under scheme is not a good choice for noisy environment where there is more probability to lose fragments in the path. In some types of applications where it does not matter if we lose some IP packets and if the network has too many traffics, mesh-under scheme should perform better than route-over scheme. If the network is ideal i.e. no packet loss at all, then mesh-under scheme is definitely better than route-over scheme in terms of the total delay or the buffer size of nodes.

6. CONCLUSION

In this paper we analyzed the probabilistic model of route-over and mesh-under routing schemes. It is concluded that route-over scheme is more reliable to deliver fragments from the source to the destination than mesh-under scheme. It is cleared that if we adopt selective retransmission in route-over and mesh-under schemes than route-over scheme will perform better than mesh-under scheme in terms of the total number of transmission. However, in case of total delay, mesh-under scheme outperformed route-over scheme. In future, we want to simulate route-over and mesh-under schemes in an IEEE 802.15.4 simulation environments and enhance their performance evaluations. We have also plan to simulate SRRO and SRMU mechanisms for route-over and mesh-under schemes.

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