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A Review of 6LoWPAN Routing Protocols

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Abstract: Internet Engineering Task Force (IETF) working group has standardized the transmission of internet protocol version 6 (IPv6) packets over IEEE 802.15.4 low power wireless personal area network (LoWPAN) as 6LoWPAN protocol. It provides the wireless sensor network (WSN) node with IP communication capabilities by putting an adaptation layer above the 802.15.4 link layer. Different mechanisms performed by adaptation layer require the 6LoWPAN header encapsulation in the packet. Although routing is among the key issues of 6LoWPAN research, the way to encapsulate a new routing header in the 6LoWPAN packet has yet been investigated thoroughly. In this paper, different ways of routing header encapsulation in 6LoWPAN protocol stack is discussed. The simplified version Ad-Hoc On-Demand Distance Vector (AODV) such as On-Demand Distance Vector (LOAD) and Dynamic MANET On-demand for 6LoWPAN (DYMO-low) have currently been proposed in 6LoWPAN routing. Hierarchical routing (HiLow) is another routing protocol that is used in 6LoWPAN to increase the network scalability. Some comparisons of these routing protocols have been made in terms of their routing metric such as number of hops count. The used control messages for the route discovery in different routing protocols have also been investigated. These comparisons show that each routing protocol has its own advantage depends on the involved applications. There are some tradeoffs of respective routing protocols. The routing protocol that uses hello message may provide more reliable but results a higher delay in the packet routing.

Keywords: WSN, IPv6, 6LoWPAN, adaptation layer, header encapsulation, routing protocol, AODV.

1. Introduction

Wireless sensor network (WSN) is one of the fastest growing segments in the ubiquitous networking today. In order to morph WSN from personal area network (PAN) into low power personal area network (LoWPAN), IEEE standard 802.15.4 is introduced [1]. The standard specifies the wireless medium access control (MAC) and physical

(PHY) layers for low-rate wireless PAN (WPAN) as defined in [2]. Currently some sensor network protocols have non-IP network layer protocol such as ZigBee, where TCP/IP protocol is not used. However, future WSNs consisting of thousands of nodes and these networks may be connected to others via the internet. Hence, IPv6 over LoWPAN (6LoWPAN) is defined by Internet Engineering Task Force (IETF) [3] as a technique to apply TCP/IP into WSN [4]. 6LoWPAN provides a WSN node with IP communication capabilities by putting an adaptation layer above the IEEE 802.15.4 link layer for the packet fragmentation and reassembly purpose [5]. The 6LoWPAN sensor nodes are the devices conform to the IEEE 802.15.4 and characterized by short range, low bit rate, low power, low memory usage and low cost [6].

With the mechanisms provided by the adaptation layer, there are four basic header types defined in 6LoWPAN: Dispatch Header, Mesh Header, Fragmentation Header and the HC1 Header (IPv6 Header Compression Header) [7]. However, beyond the Mesh Header, additional routing information is needed to be appended appropriately with the headers to achieve a full routing functionality. Therefore, additional routing header is needed to be encapsulated in the packet.

There have been a few developments on routing protocols for 6LoWPAN. In order to achieve a more lightweight protocol that maximizes bandwidth efficiency in 6LoWPAN, the 6LoWPAN Ad-Hoc On-Demand Distance Vector Routing protocol (LOAD) has been proposed in [8]. It is a simplified on-demand routing protocol based on Ad-hoc On-Demand Distance (AODV). Besides that, Dynamic MANET On-demand for 6LoWPAN Routing (DYMO-low) [9] is another 6LoWPAN routing protocol that based on DYMO. The significant feature in DYMO-low is it can support either 16-bit link layer short address or IEEE 64-bit extended address (EUI-64).

To obtain a globally unique address for preventing address conflict, both AODV and LOAD use IEEE 64-bit address as devices' interface identifiers for building on demand multi-hop routing table. However, because of its length, the IEEE address is not scalable and inefficient when used in the 6LoWPAN [10]. Therefore, hierarchical routing (HiLow) that use dynamically assigned 16-bit unique short address as device's interface identifier is proposed in [11]. It has an advantage of memory saving. The 16-bit unique short address is assigned to a 6LoWPAN device during an association operation with a neighbor device (or router) which is also called a parent node in HiLow. Besides reducing the overhead of maintaining routing table, HiLow also support for larger scalability [11]. These routing protocols have been compared in term of their routing metric and routing control messages. Each routing protocol has its own advantages and disadvantages. There are always some tradeoffs between the routing protocols. A suitable routing protocol only can be chosen based on the application that it involves.

2. 6LoWPAN Overview

6LoWPAN is a simple low cost communication network that allows wireless connectivity in applications with limited power and relaxed throughput requirements as it provides IPv6 networking over IEEE 802.15.4 networks [3]. It is formed by devices that are compatible with the IEEE 802.15.4 standard and characterized by short range, low bit rate, low power, low memory usage and low cost, where its architecture is shown in Figure 1 [12]. When a lower processing capability sensor node in a 6LoWPAN or so-called reduced function device (RFD) wants to send its data packet to an IP-enabled device outside the 6LoWPAN, it first sends the packet to the higher processing capability sensor node or so-called full function device (FFD) in the same PAN. The FFDs which react as a router in 6LoWPAN will forward the data packet hop by hop to the 6LoWPAN gateway. The 6LoWPAN gateway that connect to the 6LoWPAN with the IPv6 domain will then forward the packet to the destination IP-enabled device by using the IP address.

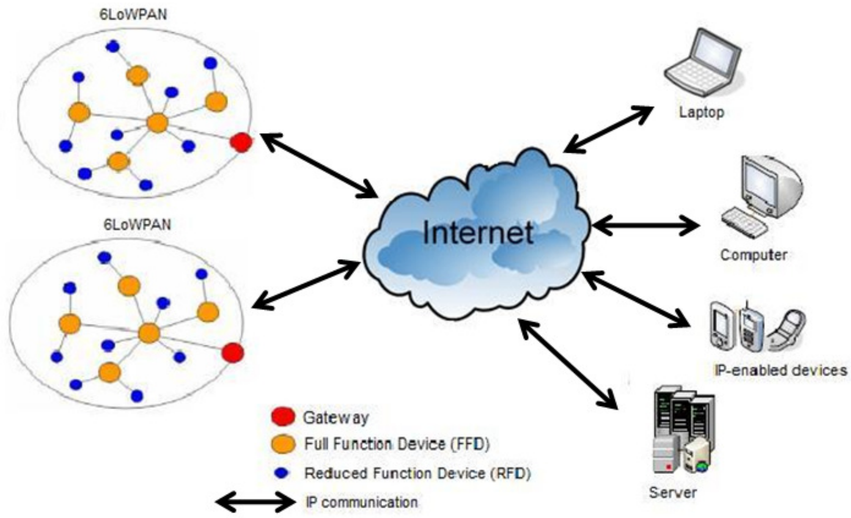

Figure 1. 6LoWPAN architecture.

Figure 2 describes the reference model of 6LoWPAN protocol stack. It adopts IEEE 802.15.4 standard PHY and MAC layers which are specified in [2], [3] as its bottom layers while chooses IPv6 in its network layer. Basically, IEEE 802.15.4 standard specifies PHY and MAC layers for low-rate wireless personal area network (LR-WPAN). The PHY layer specification dictates how the IEEE 802.15.4 devices may communicate with each other over a wireless channel. There are total of 27 channels defined in the PHY layer. These channels are allocated into different frequency bands with varying data rates as showed in Table 1. At MAC layer, it specifies when the devices may access the channel for communication. The basic tasks provided by the MAC layer are beacon generation and synchronization, supporting PAN association and disassociation, managing channel access via Carriers Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism, and etc.

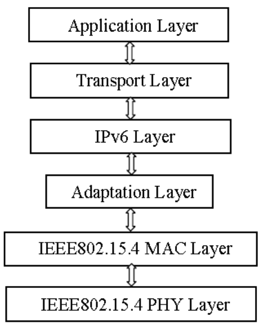

Figure 2. The reference model of 6LoWPAN protocol stack.

Table 1. Channel allocation in given frequency bands.

Frequency band (MHz)	Number of allocated channel	Data rate (kb/s)
868 – 868.6 (European)	1	20
		100 (optional)
		250 (optional)
902 – 928 (North America)	10	40
		250 (optional)
2400 – 2483.5 (Worldwide)	16	250

IEEE 802.15.4 standard defined 4 frame structures for MAC layer: beacon frame, data frame, acknowledgement frame and MAC command frame. A beacon frame is used by a PAN coordinator to transmit beacons while a data frame is used for data transfers. For the acknowledgement frame and the MAC command frame, they are used for confirming successful frame reception and handling all MAC peer entity control transfers respectively. Except acknowledgement frame which do not have MAC Service Data Unit (MSDU), other frames have the MSDU which is prefixed with a MAC Header (MHR) and appended with a MAC Footer (MFR). Figure 3 shows the general MAC frame format in the PHY frame.

The MHR comprises frame control, sequence number and address information fields while the MSDU is the MAC payload of variable length that contains the information of IPv6 packet. The MFR contains Frame Check Sequence (FCS). The MAC frame that generally formed by MHR, MSDU and MFR is then passed to the PHY as a PHY payload. The PHY payload that acts as a PHY Service Data Unit (PSDU) in a PHY frame is prefixed by a synchronization header (SHR) and a PHY header (PHR). The SHR contains the preamble and start-of-frame delimiter (SFD) fields that enable the receiver to synchronize and lock into the bit stream while the PHR contains frame length information.

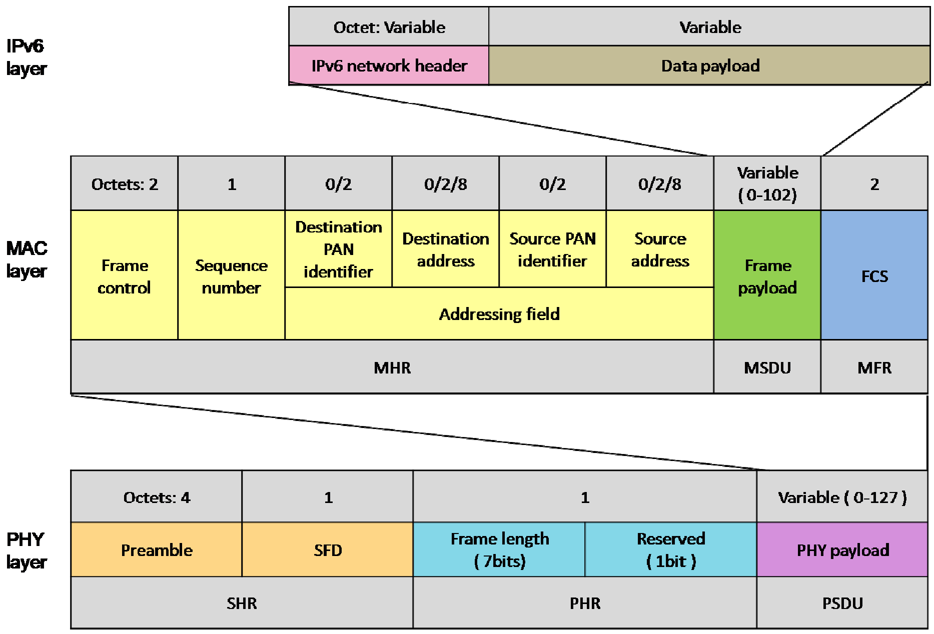

Figure 3. General MAC frame format in PHY frame.

3. Mechanisms in 6LoWPAN adaptation layer

The minimum maximum transmission unit (MTU) for an IPv6 packet over IEEE 802.15.4 is 1280 octets. However, the maximum MAC frame size defined by IEEE 802.15.4 as showed in Figure 3 is 127 bytes where 25 bytes are reserves for frame overhead and left only 102 bytes for payload. The situation becomes worse if link-layer imposes further overhead for the security purpose by adding an Auxiliary Security Header in the MAC frame, which in the maximum case leaves only 81 bytes for IPv6 packet. Thus, a full IPv6 packet does not fit in an IEEE 802.15.4 frame. Furthermore, since the IPv6 header in an IPv6 packet is 40 bytes, there is only 41 bytes left for the upper layers. Reserving either 8-bytes User Datagram Protocol (UDP) header or the 20-bytes Transmission Control Protocol (TCP) header that added at the transport layer, the IPv6 packet impractically leaves only several bytes space for the application data use. Therefore, in order to implement the seamless connection of MAC layer and IPv6 network layer, 6LoWPAN working group suggested that adding an adaptation layer between MAC layer and the network layer to achieve the header compression, fragmentation and layer-two forwarding [5], [13] – [15].

In header compression, 6LoWPAN defined HC1 encoding as an optimized compression scheme for link-local IPv6 communication. Some IPv6 header fields such as IPv6 length fields and IPv6 addresses are eliminated from a packet as long as the adaptation layer can derive them from the headers in the link-layer frame or based on simple assumption of shared context. Furthermore, the header fields that come from adaptation, network, and transport layers usually carry the common value. Hence, in order to reduce transmission overhead, header compression mechanism is used to compress those header fields to a few bits while reserving an escape value for the less common ones appear. Table 2 compares the sizes of IPv6 header fields and the 6LoWPAN compressed header fields.

Table 2. Comparison of IPv6 header and compressed 6LoWPAN header fields.

Header Field	**IPv6 header length**	**6LoWPAN HC1 length**	**Explanation**
Version	4 bits	------	Assuming communicating with IPv6.
Traffic class	8 bits	1 bit	0 = Not compressed. The field is in full size. 1 = Compressed. The traffic class and flow label are both zero.
Flow label	20 bits		
Payload length	16 bits	------	Can be derived from MAC frame length or adaptation layer datagram size (6LoWPAN fragmentation header).
Next header	8 bits	2 bits	Compressed whenever the packet uses UDP, TCP or Internet Control Message Protocol version 6 (ICMPv6).
Hop limit	8 bits	8 bits	The only field always not compressed.
Source address	128 bits	2 bits	If Both source and destination IPv6 addresses are in link local, their 64-bit network prefix are compressed into a single bit each with a value of one. Another single bit is set to one to indicate that 64-bit interface identifier are elided if the destination can derive them from the corresponding link-layer address in the link-layer frame or mesh addressing header when routing in a mesh.
Destination address	128 bits	2 bits	
HC2 encoding	------	1 bit	Another compression scheme follows a HC1 header.
Total	40 bytes	2 bytes	Fully compressed, the HC1 encoding reduces the IPv6 header to two bytes.

Fragmentation is another mechanism provided by the adaptation layer. When the IPv6 packets cannot fit into the MAC frame payload size (102 bytes of payload), the packets are fragmented into multiple link-layer frames to accommodate the IPv6 minimum MTU requirement for reassembling them at the other end. Figure 4 shows the First Fragmentation Header (4 bytes) that used in the 6LoWPAN fragmentation mechanism. The Subsequent Fragmentation Header (5 bytes) includes an extra byte for offset field. The datagram size header file is used to specify the size of the entire IP packet before adaptation-layer fragmentation. The value of this field shall be the same for all link-layer fragments of an IP packet. The datagram tag header field is used to identify all of the fragments of a single original packet. Basically, all fragments of a single packet have the same value of this field. Another header field, datagram offset field present only in the second and subsequent fragments and shall specify the offset (in increments of 8 octets) of the fragment from the beginning of the payload datagram. Actually, the implicit value of datagram offset in the first fragment is zero.

1	1	0	0	0	Datagram size (11 bits)	Datagram tag (16 bits)

Figure 4. First fragmentation header.

Besides that, in order to support layer-two forwarding of IPv6 datagrams, the adaptation layer can carry link-level addresses for the ends of an IP hop. Alternatively, the IPv6 network layer may accomplish intra-PAN routing via layer-three (adaptation layer) forwarding, in which each 802.15.4 radio hop is an IP hop. To accomplish the multi-hop packet forwarding, 6LoWPAN defined Mesh Header (4 - 5 bytes) as shown in Figure 5. Basically, the Mesh header is used to standardize the way to encode the hop limit and the link layer source and destination of the packets. Since the 802.15.4 standard support for 16-bits or 64-bits addressing mode, the value of originator (O) and the final destination (F) are one if the address is 16 bits or zero if the address is 64 bits. The "Hops left" header field is used to limit the number of intermediate hops between the source and the destination for the packet forwarding. Although "Hops left" header field can support to 15 hops constraint is enough for a common network area, the value of 0xF (all ones) was reserved to indicate that an extra byte is included to support the hop limit up to 255 hops. When there is a mesh routing or ad hoc routing in the 6LoWPAN, the sender set the originator's link-layer address in the Mesh Header to its own address and the final destination's link layer address to the packet's ultimate destination. At the same time, it also sets the source address in the MAC frame to its own link-layer address and puts the forwarder's link layer address in the destination address field of MAC frame. Finally, the sender transmits the packet. If a receiver is the final destination of the packet, it consumes the packet. Otherwise, it reduces the "Hops left" field and consults its link layer routing table to change the source address in the MAC frame as its own and the destination address in the MAC frame as the next hop towards the final destination. The packet will be discarded if the "Hop left" become zero.

1	0	O	F	Hops left (4 bits)	Originator address (16-64 bits)	Final address (16-64 bits)

1	0	O	F	0xF	Hops left (8 bits)	Originator address (16-64 bits)	Final address (16-64 bits)

Figure 5. Mesh header.

As different mechanisms in adaptation layer require different types of headers, the first two bits of the headers is used to identify the header type. As shown in the header before, bit pattern 11 is used to identify the fragmentation header while bit pattern 10 is used to identify the mesh header. In order to provide a way for coexistence with non-6LoWPAN networks, the bit pattern 00 is reserved to identify these non-6LoWPAN frames. The bit pattern 01 is used to identify the Dispatch Header. Figure 6 shows the Dispatch Header (1-2 bytes) defined in 6LoWPAN. It is used to define the type of header to follow. Figure 7 shows how the remaining 6-bit patterns that used to indicate the following header type. Only 5 of the 64 dispatch header types have thus far been defined.

0	1	Dispatch (6 bits)

0	1	0x3F	Dispatch (8 bits)

Figure 6. Dispatch header.

01	000001	The following bits are IPv6 uncompressed header
01	000010	The following bits are IPv6 HC1 compressed encoding
01	010000	The following bits are broadcast header
01	111111	The following 8 bits are an additional field for dispatch value.

Figure 7. Dispatch header bit patterns.

6LoWPAN uses the header stacking principle to separate orthogonal concepts and keep the header small and easy to parse. In other words, it means a device only uses the specific 6LoWPAN defined headers to send its packets when it is necessary. For example, when a device intends to send a short packet to a destination in a single hop, the fragmentation and the mesh header are not used in this case. The required headers will be stacked together in a specific sequence as shown in Figure 8. The header sequence is mesh addressing (if present), broadcast (if present), fragmentation (if present) and finally payload [7], [14], [15].

IEEE 802.15.4 frame	Mesh addressing	Broadcast header	Fragmentation header	Dispatch header	Compressed IP header	Payload

Figure 8. 6LoWPAN headers sequence.

With the knowledge of 6LoWPAN headers and their sequence, beyond the mesh header, additional routing information can be appended appropriately with the headers to achieve a full routing functionality. Basically, there are two routing scheme categories in 6LoWPAN: the mesh-under and the route-over. The mesh-under approach performs its routing at adaptation layer and performs no IP routing within LoWPAN whereby it is directly based on the IEEE 802.15.4 MAC addresses (16-bit or 64-bit logical address). On the other hand, the route-over approach performs its routing at network layer and performs IP routing with each node serving as an IP router The globally unique IP address of each node is created automatically by appending its interface identifier (either 16 bits or 64 bits) to the IPv6 prefix that received via router advertisement (RA). This is known as stateless auto-configuration method which is one of the 6LoWPAN features [14], [16].

Therefore, if a mesh-under routing protocol is built for operation in 6LoWPAN's adaptation layer, routing control packets with MAC addresses are placed after the 6LoWPAN Dispatch Header. Figure 9 shows the routing header encapsulation in 6LoWPAN packet format. A new Dispatch value is required to be assigned for mesh-under routing. By using the different Dispatch bit sequence, multiple routing protocols can be supported by 6LoWPAN. On the other hand, when a route-over protocol is built over IPv6 layer, the Dispatch value can be chosen as one of the pre-defined Dispatch patterns for 6LoWPAN, followed by a compressed or uncompressed IPv6 header, and route-over routing header will be included in the payload of IPv6 packet [17].

Dispatch Header (new 6-bit sequence)	Routing header	Payload

Figure 9. Routing header encapsulation in 6LoWPAN packet format.

4. Comparisons of existing 6LoWPAN routing protocols

Due to the constrained resources of 6LoWPAN devices, routing protocols in 6LoWPAN environments make the choice from existing pool of routing schemes very limited. AODV has been considered as a strong candidate for 6LoWPAN due to its simplicity in finding route. However, some modification must be done in AODV in order to suit it into 6LoWPAN environments. In this Section, two 6LoWPAN routing protocols, LOAD and DYMO-low which based on AODV routing scheme are discussed. Besides that, routing protocols such as HiLow also be discussed. The comparison of all three existing routing is populated in the Table 3 of this section.

4.1 6LoWPAN Ad-Hoc On-demand Distance Vector Routing (LOAD)

LOAD protocol is a simplified on-demand routing protocol based on AODV [8]. It is defined to be operating on top of the adaptation layer instead of the transport layer. It creates a mesh network topology underneath and unbeknownst to IPv6. IPv6 sees a 6LoWPAN as a single link. Additionally, it should be only run on FFDs. LOAD does not use the destination sequence number that used in AODV. For ensuring loop freedom, only the destination of a route should generate a Route Reply (RREP) in reply. The accumulated route cost such as LQI and the number of hops from the source to the destination are the routing metrics in LOAD. A route is preferred if the number of weak links along the way is smaller (link whose LQI is worse than a certain threshold value) and less hops from the source to the destination. Besides that, LOAD does not use the precursor list of AODV in order to simplify the routing table structure. Precursor lists are used in AODV to forward Route Error (RERR) messages in case of a broken link along the route of a data message happens or if the next hop to the destination cannot be found in the routing table.

In LOAD, when there is a link break, the upstream node of the link break may try to repair the route locally by using route discovery mechanism in LOAD whereby broadcasted Route Request (RREQ) and unicast RREP message are used. If the repairing node unable to repair to link, it unicasts a RERR with an error code that indicates the reason of the repair failure to the originator of the failed data message only. Thus no requiring any precursor list as used in AODV for forwarding the RERR messages. Unlike AODV, LOAD uses the link layer acknowledgements instead of Hello messages to save energy while keeping track of route connectivity. It requests MAC layer acknowledgement for every sent data message and is termed as Link Layer Notification (LLN) [21], [22]. Figure 10 shows the LOAD protocol message exchange.

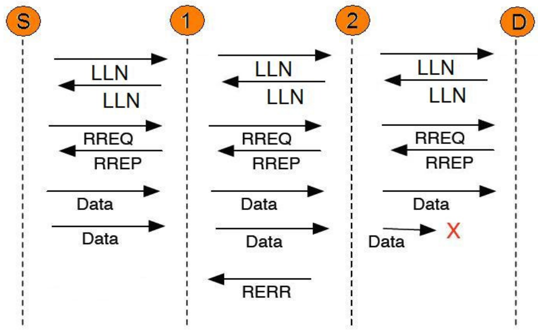

Figure 10. LOAD protocol message exchange.

4.2 Dynamic MANET On-demand for 6LoWPAN Routing (DYMO-low)

The DYMO protocol is based on AODV that provides an effective and simple to implement routing protocol. Like AODV, DYMO performs route discovery and maintenance by using RREQ, RREP and RERR messages. During route discovery, RREQ and RREP messages accumulate routing information from each intermediate node. Unlike AODV, the DYMO protocol does not use local repair although it uses Hello message to keep track of the link connectivity. DYMO is positioned on top of IP, using User Datagram Protocol (UDP) as the underlying protocol. However, it cannot be directly applied in 6LoWPAN routing due to its increased memory and power consumption. Thus, DYMO-low is proposed in [9] to suit DYMO into the 6LoWPAN environment. Instead of using the IP layer, DYMO-low operates on the link layer directly to create a mesh network topology of 6LoWPAN devices unbeknownst to IP, such that IP sees the WPAN as a single link. All the 6LoWPAN devices on that WPAN are on the same IPv6 link, sharing the same IPv6 prefix. DYMO-low uses 16-bit link layer short address or IEEE 64-bit extended address (EUI-64). All of the features that discussed in LOAD above are used in DYMO-low except that the 16-bits sequence numbers are used in DYMO-low to ensure loop freedom. Besides that, local repair and route cost accumulation that used in LOAD are no used as well in DYMO-low.

4.3 Hierarchical routing (HiLow)

In order to increase the network scalability, HiLow is proposed for 6LoWPAN. Figure 11 shows the HiLow routing structure. Unlike AODV and LOAD that use IEEE 64-bit identifier, HiLow use 16-bit unique short address as interface identifier for memory saving and larger scalability. In HiLow, when a IEEE 802.15.4 device (or child) want to join a 6LoWPAN, it first tries to discover an existing 6LoWPAN by scanning procedures. If there is no 6LoWPAN in its personal operating space (POS), the child device becomes the initiator (or coordinator) of a new 6LoWPAN and assigns its short address by 0. Otherwise, the child device can find an existing neighbor device (or parent) of the existing 6LoWPAN and tries to associate with the parent at the MAC layer to receive a 16-bit short address. Every child node receives a short address by the following equation

$$C = MC * AP + N \qquad (0 < N \leq MC) \qquad (1)$$

where C is the child node address, MC is the maximum number of children a parent can have, AP is the address of the parent, N is the nth child node.

For the routing operation in HiLow, it is assumed that every node knows its own depth. When a node receives an IPv6 packet, it is called the current node. The current node determines first whether it is either the ascendant or descendant nodes of the destination by using (1), whereby in this case, C is the address of the current node and AP is the address of the parent of the current node. After that, the current node determines the next hop node to forward the packet by using the algorithm in [11]. However, when there is a link break in a route, HiLow does not support any recovery path mechanism as AODV and LOAD.

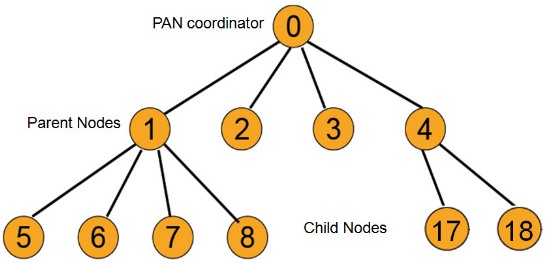

Figure 11. HiLow routing structure.

Table 3. Comparisons of 6LoWPAN routing protocols.

	AODV (WSN)	**LOAD**	**DYMO-low**	**HiLow**
RERR message	Use	Use	Use	No use
Sequence number	Use	No use	Use	No use
Precursor list	Use	No use	No use	No use
Hop count	Use	Optional	Optional	Use
Hello message	Use	No use	Use	No use
Local repair	Use	Use	No use	No use
Energy Usage	High	Low	Low	Low
Memory usage	High	Medium	Medium	Low
Mobility	Mobile	Mobile	Mobile	Static
Scalability	Low	Low	Low	High
Routing delay	High	Low	High	Low
Convergence to topology change	Fast	Fast	Fast	Slow

5. Conclusions

In this paper, different types of 6LoWPAN headers are discussed. With the knowledge of the 6LoWPAN header encapsulation, it is possible to encapsulate the new routing header in the 6LoWPAN packet to achieve full routing functionality. The existing routing protocols in 6LoWPAN such as LOAD, DYMO-low and HiLow are reviewed. Some comparisons of the routing protocols have made in term of their routing metric such as hop count. The control messages that used for route discovery in different routing protocols have also be investigated. The comparisons show that each routing protocols has its own advantages depends on the application it involves. There are some tradeoffs in the respective routing protocols such as routing protocol that uses hello message may give a more reliable but higher delay in the packet routing. Although HiLow gives an advantage of memory saving to provide a larger scalability, its convergence to network topology change is slower compared to LOAD and DYMO-low. This will induce more delay for the route discovery process in HiLow.

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