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6LOWPAN HEADER COMPRESSES WITH END-TO-END HYBRID ROUTE-OVER USING CROSS-LAYER AND ADAPTIVE BACKOFF EXPONENT

SAMER ADNAN ALI BANI AWWAD

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By

SAMER ADNAN ALI BANI AWWAD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

قال تعالى:

((وَوَصَّيْنَا الإِنسَانَ بِوَالِدَيْهِ حَمَلَتْهُ أُمُّهُ وَهْناً عَلَى وَهْنٍ وَفِصَالُهُ فِي عَامَيْنِ أَنْ اشْكُرْ لِي وَلِوَالِدَيْكَ إِلَيَّ الْمَصِيرُ))

لقمان 14

To the most Merciful Allah S.W.T.

To My Family and Friends

My encouraging and beloved parents (Adnan Ali Bani Awwad and Fatimah Ahmad Bani Awwad),

My dear wife (Noor),

My beloved daughters (Fatimah, Sarah and Sayimaa), and my dear son Abd-Alrahman

My parents in-laws (Ismail Omar and Noraini Omar),

My brothers and sisters in Jordan and Malaysia,

My friends.

And to my homeland, Jordan.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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SAMER ADNAN ALI BANI AWWAD

April 2016

Chairman : Professor Nor Kamariah binti Noordin, PhD
Faculty : Engineering

In the world of Internet of Things (IoT) and wireless embedded internet, the IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) was specifically introduced to enable IPv6 global internet connectivity for Low-Power Wireless Personal Area Network (LOWPAN). However, this requires the LOWPAN embedded devices to run IPv6 protocol. On the other hand, enabling IPv6 protocol for embedded devices is not directly applicable due to limited IEEE 802.15.4 frame size, huge headers sizes and routing challenges.

In 6LoWPAN, the headers such as TCP, UDP, IPv6 and IEEE 802.15.4 have relatively huge sizes. This depletes the frame payload to approximately 33 bytes. Some techniques are designed to compress the packet's headers and provide more space for actual data payload. These compression techniques individually compress each fragment in the packet, and hence similar redundant headers are carried by these fragments. In this thesis, a compression scheme called Second and Subsequent Fragments Headers Compression (S&SFHC) for 6LoWPAN network is presented. The S&SFHC scheme exploits the correlation between the first and the subsequent fragments' headers, hence the redundant headers are not carried again by the second and subsequent fragments. The S&SFHC scheme can work either as a standalone or be integrated with other compression techniques. The S&SFHC standalone mode achieves up to 40% higher packet delivery ratio, 12% lower average delay and 35% lower average energy consumption compared to LOWPAN Internet Protocol Header Compression (LOWPAN_IPHC). Furthermore, in integrated mode, where S&SFHC and LOWPAN_IPHC are integrated together, it achieves up to 30% higher packet delivery ratio, 20% lower average delay and 24% lower average energy consumption compared to the LOWPAN_IPHC when packet size grows up to 600 bytes.

The thesis also presents a hybrid Route-Over routing protocol with End-to-End fragmentation and reassembly using Adaptive Backoff Exponents (ROE2E-ABE). In this protocol, end-to-end fragmentation and reassembly is adopted to reduce the average end-to-end delay, while an adaptive backoff exponents mechanism is adopted to maintain high packet delivery ratio. This protocol can avoid both the high packet loss rate of enhanced route-over which happens due to collision, and the high average end-to-end delay of conventional route-over which happens due to hop-by-hop fragmentation and reassembly. Hence, this protocol enjoys both advantages of high packet deliver ratio of conventional route-over routing and low average end-to-end delay of enhanced route-over routing. The ROE2E-ABE achieves up to 23% higher packet delivery ratio over that of route-over with hop-by-hop fragmentation and reassembly when the packet size is increased to 600 bytes. In addition, it achieves up to 80% lower average end-to-end delay compared to route-over with end-to-end fragmentation and reassembly while achieving higher throughput and lower average energy consumption.

Both S&SFHC and ROE2E-ABE have been integrated. This results in up to 10% higher packet delivery ratio, 17% lower average end-to-end delay, 10% higher total throughput and 13% lower average energy consumption than ROE2E-ABE without S&SFHC integration.

Finally, the thesis presents a mathematical performance analysis for conventional route-over, enhanced route-over and ROE2E-ABE routing protocols in terms of packet delivery ratio, average end-to-end delay and average energy consumption.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

MAMPATAN HEADER 6LOWPAN DENGAN HIBRID LALUAN-LEBIH HUJUNG-KE-HUJUNG MENGGUNAKAN LAPISAN-SEBERANG DAN PENYESUAIAN BELAKANG EKSPONEN

Oleh

SAMER ADNAN ALI BANI AWWAD

April 2016

Pengerusi : Profesor Nor Kamariah binti Noordin, PhD
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Dalam dunia Internet of Things (IoT) dan wayarles terbenam dalam internet, IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) diperkenalkan untuk membolehkan sambungan internet IPv6 secara global bagi Low-Power Wireless Personal Area Network (LOWPAN). Walau bagaimanapun, hal ini memerlukan peranti terbenam LOWPAN untuk mengendalikan protokol IPv6. Namun begitu, membenarkan protokol IPv6 dan peranti terbenam sahaja adalah tidak sesuai kerana saiz bingkai IEEE 802.15.4 yang terhad, saiz header yang besar serta beberapa cabaran dalam isu penghalaan.

Dalam 6LoWPAN, saiz header seperti TCP, UDP, IPv6 dan IEEE 802.15.4 adalah agak besar. Oleh itu, muatan bingkai berkurangan sehingga 33 bait. Beberapa teknik telah direka untuk memampatkan paket header tersebut dan menyediakan lebih banyak ruang untuk muatan data sebenar. Teknik pemampatan adalah untuk memampatkan setiap fragmen dalam paket dan seterusnya header yang sama ini dibawa oleh fragmen sedia ada. Dalam tesis ini, skema pemampatan Second and Subsequent Fragments Headers Compression (S&SFHC) untuk rangkaian 6LoWPAN telah dibentangkan. Skema S&SFHC mengeksploitasi kolerasi antara fragmen yang pertama dan header fragmen yang seterusnya. Justeru itu, header berulang tidak akan dibawa sekali lagi dalam fragmen kedua dan fragmen berikutnya. Skema S&SFHC boleh bekerja secara kendiri atau disepadukan dengan teknik pemampatan yang lain. Mod kendiri S&SFHC mencapai sehingga 40% nisbah penghantaran paket lebih tinggi, 12% purata lengahan lebih rendah dan 35% purata penggunaan tenaga lebih rendah berbanding LOWPAN Internet Protocol Header Compression (LOWPAN_IPHC). Tambahan pula, dalam mod bersepadu, iaitu S&SFHC dan LOWPAN_IPHC mencapai sehingga 30% nisbah penghantaran paket lebih tinggi, 20% purata lengahan lebih rendah dan 24% purata penggunaan

tenaga lebih rendah berbanding LOWPAN_IPHC tersebut apabila saiz paket meningkat sehingga 600 bait.

Tesis ini juga membentangkan protokol hibrid iaitu Route-Over routing protocol with End-to-End fragmentation and reassembly using Adaptive Backoff Exponents (ROE2E-ABE). Dalam protokol ini, fragmentasi dan penstrukturan semula hujung-ke-hujung diadaptasi bagi mengurangkan purata lengahan hujung-ke-hujung, dan dalam masa yang sama mekanisma Adaptive Backoff Exponents direka untuk mengekalkan nilai nisbah penghantaran paket yang tinggi. Protokol ini boleh mengelakkan dua keadaan iaitu; kadar kehilangan paket yang tinggi bagi protokol penghalaan route-over tambahan yang berlaku akibat perlanggaran, dan purata lengahan hujung-ke-hujung yang tinggi bagi protokol penghalaan route-over konvensional yang berlaku disebabkan oleh fragmentasi dan penstrukturan semula hop-ke-hop. Oleh itu, protokol ini mewarisi kelebihan kedua-dua nisbah penghantaran paket yang tinggi dan purata lengahan hujung-ke-hujung yang rendah bagi protokol penghalaan route-over tambahan. Protokol ROE2E-ABE mencapai 23% nisbah penghantaran paket lebih tinggi berbanding protokol fragmentasi dan penstrukturan semula route-over hop-ke-hop apabila paket meningkat kepada 600 bait. Di samping itu, ia mencapai sehingga ke 80% lebih rendah bagi purata lengahan hujung-ke-hujung berbanding fragmentasi dan penstrukturan semula route-over hujung-ke-hujung sambil mencapai kadar celus yang lebih tinggi dan purata penggunaan tenaga yang lebih rendah.

Kedua-dua skema S&SFHC dan protokol penghalaan ROE2E-ABE direkabentuk dan telah disepadukan. Hasilnya, menncapai sehingga 10% nisbah penghantaran paket lebih tinggi, 17% purata lengahan hujung-ke-hujung lebih rendah, 10% nilai kadar celus lebih tinggi dan 13% purata penggunaan tenaga lebih rendah daripada ROE2E-ABE tanpa disepadu dengan mekanisma S&SFHC.

Akhirnya, tesis ini juga telah membentangkan analisis matematik untuk protokol penghalaan route-over konvensional, route-over tambahan dan ROE2E-ABE dari segi nisbah penghantaran paket, purata lengahan hujung-ke-hujung, dan purata penggunaan tenaga.

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I certify that a Thesis Examination Committee has met on 26 April 2016 to conduct the final examination of Samer Adnan Ali Bani Awwad on his thesis entitled "6LoWPAN Header Compresses with End-To-End Hybrid Route-Over Using Cross-Layer and Adaptive Backoff Exponent" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ABE	Adaptive Backoff Exponents
ACK	Acknowledgment
AES	Advance Encryption Standard
BEs	Backoff Exponents
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
C-MUR	Chained Mesh-Under Routing
Direct-ARR	Direct Mode with Adaptive Rate Restriction
Direct-RR	Direct Mode with Rate Restriction
FUIList	Free Unique Identifier List
FFDs	Full Function Devices
ICMP	Internet Control Message Protocol
IoT	Internet of Things
LOWPAN _IPHC	LOWPAN IPv6 Header Compression
IP	Internet Protocol
IPSec	IP Security
6LoWPAN	IPv6 over Low Power Wireless Personal Area Network
IPv6	Internet Protocol version 6
LLC	Link Layer Control
LUI	Link Unique Identifier
LTE	Long Term Evolution
LoWPAN_HC1	LOWPAN Header Compression 1
LoWPAN_HC1g	LOWPAN Stateless IPv6 Header Compression for Globally Routable Packets
LoWPAN_HC2	LOWPAN Header Compression 2

LoWPAN_NHC	LOWPAN Next Header Compression
MAC	Media Access Control
MaxBE	Maximum Backoff Exponent
MaxCSMABackoffs	Maximum CSMA Backoffs
MinBE	Minimum Backoff Exponent
NACK	Negative Acknowledgement
PSTN	Public Switched Telephone Network
RFID	Radio-Frequency Identification
RFDs	Reduced Function Devices
RFC4944	Request for Comments 4944
ROHC	Robust Header Compression
ROE2E-ABE	Route-Over routing protocol with End-to-End fragmentation and reassembly using Adaptive Backoff Exponent
RTP	Real-time Transport Protocol
S&SFHC	Second and Subsequent Fragments Headers Compression
SRMU	Selective Retransmission for Mesh-Under
SRRO	Selective Retransmission for Route-Over
SNMP	Simple network management protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
TANs	Temporary Assembling Nodes
UDP	User Datagram Protocol
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

CHAPTER 1

INTRODUCTION

The main enabling factor of Internet of Things (IoT) is the integration of several technologies within the internet [1-3]. The IPv6 over Low Power Wireless Personal Area Network (6LoWPAN) is one of the main communication technologies that needs to be integrated with other technologies under IoT umbrella [4-6]. The 6LoWPAN was introduced to enable the transmission of IPv6 packets over Low-Power Wireless Personal Area Network (LOWPAN) [7, 8]. The 6LoWPAN has three main drawbacks [7, 8]; first, the fragmentation and reassembly of the relatively large IPv6 packet in order to be carried by the IEEE 802.15.4 small frames. Second, header compression to compress the relatively huge header of upper layer like IP and transport layer headers to enable efficient data transmission. Third, routing protocol to forward the fragmented or un-fragmented IPv6 packets through multiple hops toward its intended destination. Although, the first drawback can be simply handled through supporting fragmentation and reassembly of IPv6 packets, the other two drawbacks still quench for intense research interest.

This chapter presents an overview of the research aspects and architecture. The background of the header compression schemes and routing protocols in 6LoWPAN is presented. The drawbacks in the existing relevant research are highlighted. Then, the problem statement that motivated conducting this research is presented. The research scope is then discussed before presenting the research aim and objectives. The research contributions are then enlisted before ending the chapter with the thesis organization.

1.1 Header Compression and Routing Protocols in 6LoWPAN: Research Background, Drawbacks and Motivations

The header is the supplemental portion of the packet that precedes the payload. It contains transporting, addressing, error detection and error correction information, and other important data that are required to correctly transmit the packet to its final destination [9, 10]. When the header size is relatively big, it is significantly degrading the network performance [11, 12]. In 6LoWPAN, introducing IPv6 protocol over IEEE 802.15.4 small frame size depletes the frame payload; leaving few bytes for the actual data [7, 13]. Hence, header compression was introduced as a solution to compress the huge headers of transport, IP and adaptation layers [7]. This provides more bytes for actual data.

A few header compression techniques had been introduced for 6LoWPAN. The LOWPAN Header Compression 1 (LOWPAN_HC1) and LOWPAN Header Compression 2 (LOWPAN_HC2) were the first IPv6 and UDP header compression schemes proposed for 6LoWPAN [7]. In these schemes, some of the IPv6 and UDP headers' fields are compressed to predefined values like the IP version field, while some other fields are represented using a lower number of bits like the source and destination ports' fields. In contrast, some fields remain uncompressed like hop limit field. The source and destination addresses are compressed based on the link layer addresses.This scheme can compress only IPv6 link local addresses where the source and destination addresses are stateless configured link-local addresses. Hence, it cannot compress the global IPv6 addresses. LOWPAN Stateless IPv6 Header Compression for Globally Routable Packets (LoWPAN_HC1g) [14] is an extension of LoWPAN_HC1. It is designed to compress IPv6 global addresses. However, this scheme assumes that 6LoWPAN network is assigned a default, single, compressible and global address prefix. When the source or destination addresses' prefixes match the default one, they can be compressed. Otherwise the global address prefix remains uncompressed.

LOWPAN IPv6 Header Compression (LOWPAN_IPHC) [15] extended the capability of LOWPAN_HC1. In addition to link-local addresses, it can also compress global unicast addresses by assuming a conceptual context of a small and limited set of routable prefixes is assigned to 6LoWPAN nodes within the entire network. This compression scheme expects that the conceptual context is shared between the node that compresses the packet, and the node(s) that need(s) to expand it. However, how the contexts of limited prefixes are shared and maintained, and what information is contained within the context information was not determined by the scheme.

The 6LoWPAN header compression is tightly connected with the fragmentation and reassembly [16]. However, none of the discussed header compression schemes had considered the fragmented packet. They perform the header compression apart from packet fragmentation and reassembly that occurs when the packet is too big and cannot fit within a single IEEE 802.15.4 frame. Hence, when IPv6 packet is fragmented, these techniques handle the second and the subsequent fragments similarly to the first one. This means that similar headers are carried in each fragment; the second and subsequent fragments need to carry similar uncompressed or partially compressed header which is, in many scenarios, still consider huge. This increases the number of fragments and then, reduces the probability of successful packet delivery [17] and increases the inter fragment interference between these fragments [18]. Therefore, the average packet delivery ratio and average throughput are reduced while the average delay and the average energy consumption are increased.

In 6LoWPAN, routing protocols are also tightly connected to both header compression and packet fragmentation and reassembly. These protocols govern when and where the fragmented packet is reassembled based on which routing protocol is used; route-over or mesh-under [17, 19]. Hence, they control when the decompression occurs either hop-by-hop or end-to-end basis. In order to route a fragmented packet using route-over, either one of the following two choices should be adopted. First, the whole compressed or uncompressed header is presented in each fragment. In this case, each fragment can be routed separately using different routes. Second, if the header is not presented in each fragment, all packet's fragments should follow the same route and the fragments could be reassembled per hop basis to retrieve the required information for routing decision. Hence, header compression could be interrupted by the routing protocol.

Selective fragment retransmission recovery mechanisms for route-over, called Selective Retransmission for Route-Over (SRRO), had been proposed and analyzed in [17]. The mechanism works based on a selective Negative Acknowledgement (NACK) that is sent from the receiver (next hop node) to the sender (previous node). Consequently, only the lost fragments are retransmitted for a single hop. In addition, an extension to Request for Comments 4944 (RFC4944) was proposed in [20] to support a fragment recovery mechanism. In a few numbers of hops and a few numbers of fragments scenarios, selective retransmission may slightly increase the average packet delivery ratio in route-over routing protocol. However, in a high number of hops and a high number of fragments scenarios, fragments' retransmissions increase the contentions and the inter fragment interference and hence, the collisions between fragments are increased accordingly. Furthermore, the main drawback of route-over, which is the high average end-to-end delay, is still unsolved.

A hybrid routing protocol called Chained Mesh-Under Routing (C-MUR) protocol was introduced to overcome the main mesh-under routing drawback of low packet delivery ratio [21]. In order to overcome this problem, C-MUR partially adopts a route-over approach. It suggests to reassemble the packets at some selected intermediate forwarders, called Temporary Assembling Nodes (TANs). The C-MUR protocol increases the packet delivery ratio through decreasing the collision that may happen between the intermediate forwarders. Reassembling the packet at the TANs decreases the inter fragment interference between the intermediate forwarders. However, the TANs intermediate forwarders that accomplish the reassembling process need to be selected carefully. Increasing the packet deliver ratio is related to the increment of TANs intermediate forwarders that reassemble the packet. However, increasing the TANs has the impact of increasing the average end-to-end delay, especially when the number of fragments is high. If the none TANs intermediate forwarders loss a single fragment, the whole packet is lost. Furthermore, when the traffic or the number of fragments are high, the inter fragment interference is increased and hence, the collision increases as well.

A modified route-over technique had been proposed in [22]. The introduced technique aims to overcome the two main shortcomings of route-over routing protocol; the hop-by-hop fragmentation and reassembly and the retransmission of the whole fragments within a single hop in case one or more fragments are lost. In this technique, the intermediate forwarder avoids hop-by-hop fragmentation and reassembly by only buffering and queuing the fragments until all of them are received, then it starts transmitting them again without reassembling the original packet. The technique avoids retransmitting the whole fragments by implying selective retransmission for the lost fragments. In order to confirm performance of the technique, the technique needs to be tested using a higher number of hops between the source and destination [23]. However, although the fragments are not reassembled at the intermediate forwarders, the fragments are buffered and queued in each intermediate forwarder until the whole packet's fragments are received then the forwarding process is resumed. This consumes the memory and significantly increases the queuing delay, especially when the number of intermediate forwarders and the number of fragments are high. The work does not address the inter fragment interference that increases when the traffic, the number of fragments or the retransmission rate are high. Furthermore, when the node is entering retransmission state directly after a collision. The inter fragment interference between the fragments increases. This interference leads to high collisions and decreases the packet delivery ratio.

Route-over routing protocol had been enhanced in [16]. In this enhanced route-over, the hop-by-hop fragmentation and reassembly is avoided and hence, the average end-to-end delay is reduced. In this route-over protocol, the intermediate routers establish a virtual circuit to forward the second and the subsequent fragments by storing both the IPv6 and fragmentation headers of the first fragment. This enables the fragments to be forwarded directly without being reassembled at each intermediate router. However, when the traffic, the number of fragments or the number of hops between source and destination are high, the contention and the inter fragment interference are increasing as well. Intermediate forwarders transmissions of different fragments may interfere. Thus, the collisions between the fragments are increasing as well. This will significantly decreases the packet delivery ratio and throughput and increases the average energy consumption.

In [23], route-over had been enhanced to control high average end-to-end delay through avoiding hop-by-hop fragmentation and reassembly. Also, the work addressed the inter fragment interference by introducing two different rate-restriction mechanisms (static and adaptive) that adds a delay between the successive transmissions of fragments, which yield to reduce the collision caused by the hidden terminal problem. The paper uses a single hop link layer retransmission of a single fragment to avoid end-to-end retransmission of the whole packet. However, the introduced transmission delay does not consider the parameters that cause the collision; number of fragments and number of hops between the source and destination. Furthermore, in high traffic, high number of fragments and high number of hops between the source and destination, the high retransmission rate leads to increase the overhead, contention and the inter fragment interference and hence, increases the collisions between the intermediate forwarders transmissions. In this environment, the inter fragment interference between fragments of the same packet, which is called the self-interference as well, aggravates the problem [18]. As the work concluded, high retransmission rate proved its insufficiency in increasing the packet delivery ratio [23]. As the paper reveals, the packet received ratio for both modes could be slightly increased by the introduced re-try control. The presented work in [23] states that the impact is not as large as hoped [23]. This result is expected based on the research's outcome in [17]. The probability of successful transmission when the number of retries equals to three is almost 99%. This points that the successful transmission will be slightly enhanced after three retransmission retries.

1.2 Problem Statement

Based on the header compression techniques and routing protocols drawbacks presented in Section 1.1, the problem statement can be addressed as follows:

1. The header compression of fragmented IPv6 packet is not handled efficiently. The existing header compression schemes just consider either un-fragmented packet or the first fragment of a fragmented IPv6 packet only. There is no special consideration for the second and the subsequent fragments of a fragmented packet. This means that either similar headers are carried in each of the second and the subsequent fragments or all packet's fragments are forced to follow the same route and perform per hop packet reassembly to be able to perform a routing decision.

2. Several header compression techniques had been introduced to compress various headers types of IPv6 packet. The integration between these header compression techniques, when applicable, gives higher compression ratio, lower number of fragments, lower collision rate, and hence higher packet delivery ratio and lower average delay. However, many of these headers compression techniques lack the capabilities of being integrated with others. The lack of integration between these compression techniques limits the compression capabilities of them. This leads to lower compression ratio, higher number of fragments, higher collision rate, and hence low packet delivery ratio and high average delay.

3. Even though route-over achieves a high packet delivery ratio, it inherits the drawback of high average end-to-end delay. Hop-by-hop fragmentation and reassembly implies additional queuing, processing, reassembling and fragmenting delays at each intermediate router. This significantly increases the average end-to-end delay of IPv6 packet when it is forwarded between the source and final destination. Although enhanced route-over reduces the average end-to-end delay through avoiding hop-by-hop fragmentation and reassembly, it drastically increases the inter and intra fragments interferences. The interferences are increased, especially when the fragmented IPv6 packet has a high number of fragments, the route between the source and the destination has a high number of hops or when the traffic in the network is high. This increases the collision and hence, reduces the average packet delivery ratio and average throughput while increasing the average energy consumption.

   Reassembling IPv6 packet at specific intermediate forwarders can achieve moderate average packet delivery ratio while maintaining moderate average end-to-end delay between route-over and mesh-under. However, the TANs intermediate forwarders that accomplish the reassembly process need to be selected carefully. Increasing the average packet deliver ratio is related to the increment of TANs intermediate forwarders that reassemble the packet. On the other hand, increasing the TANs has the impact of increasing the average end-to-end delay, especially when the number of fragments and the number of hops between source and destination are high. If any intermediate forwarder loses a single fragment, the whole packet is lost. Furthermore, when the traffic or the number of fragments are high, the inter fragment interference increases and thus the collision increases as well.

The attempt to increase the packet delivery ratio through increasing the retransmission rate may aggravate the problem, especially when both the number of fragments and the number of hops between the source and destination are high. It increases the overhead, contention, inter fragment interference and collisions between the intermediate forwarders transmissions. Hence, it may give a reverse impact on the average packet delivery ratio, average throughput, average end-to-end delay and average energy consumption.

4. Header compression schemes and routing protocols are designed separately from each other. So, the enhancement in one of them may significantly hurt the other. When enhanced route-over avoids hop-by-hop fragmentation and reassembly, it necessities each fragment to carry uncompressed or partially compressed header to enable the fragment to be routed separately and independently from other fragments. Therefore, upper layers' headers (IP header, UDP) need to be presented in each fragment. On the other hand, route-over with hop-by-hop fragmentation and reassembly enables efficient header compression since the IP and the transport layer headers are carried by the first fragment only. Consequently, creative and comprehensive design method that considers both route-over with end-to-end fragmentation and reassembly and header compression for second and subsequent fragments should be presented.

1.3 Aim and Objectives

The aim of this research is to design 6LoWPAN cross-layer route-over routing protocol with end-to-end fragmentation and reassembly while supporting header compression. In order to achieve this aim, the following objectives have been accomplished:

1. Design, implement and evaluate the Second and Subsequent Fragments' Headers Compression (S&SFHC) scheme to compress the relatively huge headers of the fragmented IPv6 packet in 6LoWPAN network by compressing the header of the second and subsequent fragments.

2. Extend the S&SFHC scheme to support integrated mode and evaluate both, standalone and integrated, modes in terms of packet delivery ratio, average delay, total throughput and average energy consumption compared to LOWPAN_IPHC and LOWPAN Next Header Compression (LOWPAN_NHC) techniques.

3. Design and implement cross-layer and hybrid Route-Over routing protocol with End-to-End fragmentation and reassembly using Adaptive Backoff Exponents (ROE2E-ABE) and then, evaluate and analyze the designed protocol compared to both, conventional and enhanced route-over routing protocols in terms of packet delivery ratio, average end-to-end delay, average throughput and average energy consumption.

4. Integrate the ROE2E-ABE routing protocol with S&SFHC scheme and evaluate their overall performance based on the given performance metrics.

1.4 Thesis Scope

The wireless personal area network is wireless, low power, low rate and battery operated with limited communication and computation capabilities network. It had initially been designed as a standalone network where the data is collected to a static gateway. Connecting WPAN to the IoT adds many advantages to it. However, IoT requires the WPAN devices to have an internet protocol address. IPv6, the new version of internet protocol, is used to provide addresses and an internet connectivity to this network forming 6LoWPAN network.

The 6LoWPAN supports the connection of LoWPAN to the IoT. Figure 1.1 shows the scope of this thesis. As the figure shows, the integration between WPAN and IPv6 in 6LoWPAN enforces mainly three new networking requirements. First, headers compression for the relatively huge headers of IP based network. Second, fragmentation and reassembly to the large IPv6 packets that cannot fit within a single IEEE 802.15.4 frame. Third, routing protocol development based on either route-over routing protocols that are inherited from IPv6 network or mesh-under routing protocols. In this research, these requirements are considered since they are tightly connected. The scope of this thesis contribution is highlighted by the shaded components.

The S&SFHC, a new header compression technique, has been introduced to compress the second and subsequent fragments' headers for fragmented IPv6 packet. In addition, ROE2E-ABE, a cross-layer route-over routing protocol with end-to-end fragmentation and reassembly using adaptive backoff exponents has been developed as well. Finally, the S&SFHC technique and the ROE2E-ABE routing protocol are integrated to enhance the overall performance of the 6LoWPAN.

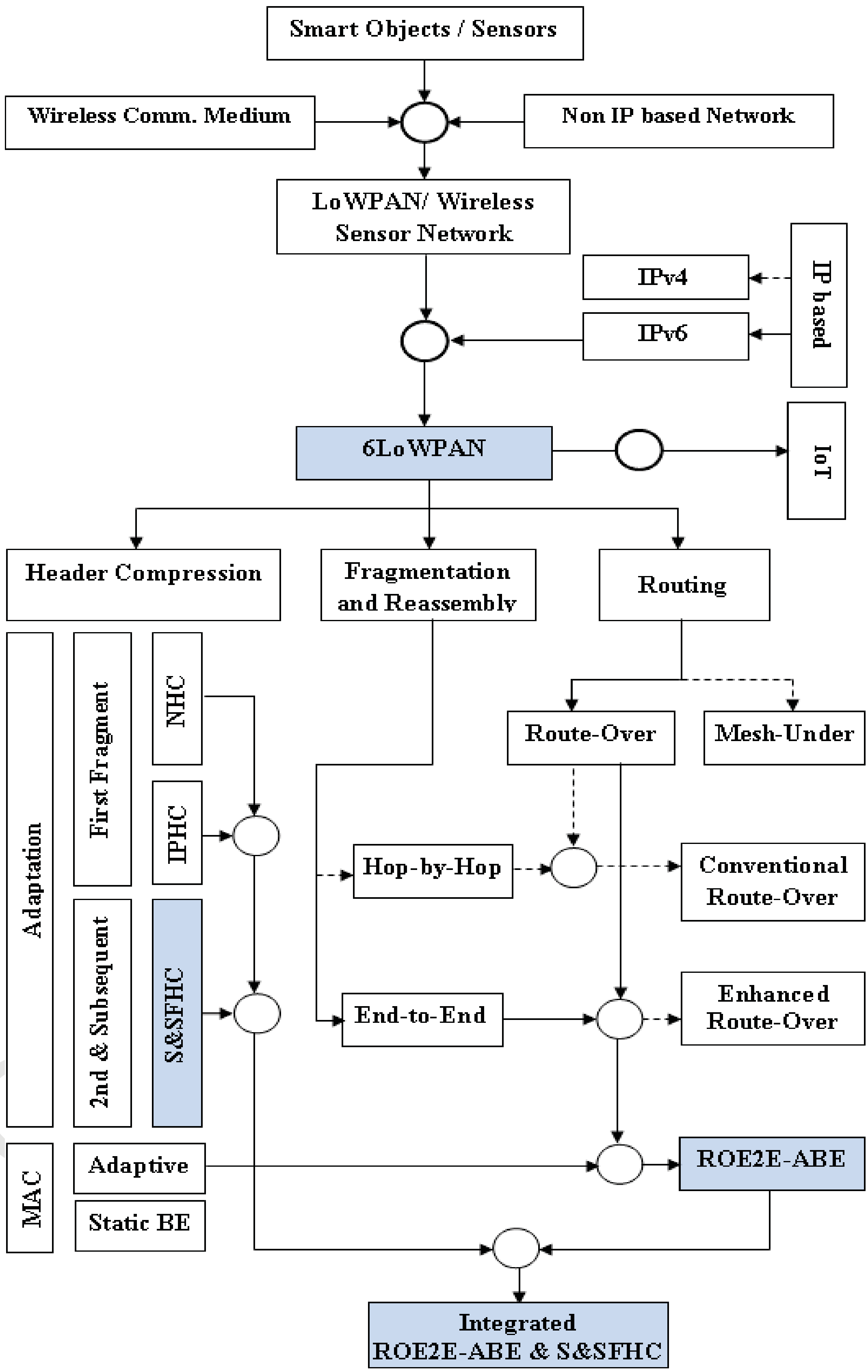

Figure 1.1 : Thesis Scope

1.5 List of Thesis Contributions and Findings

The research contributions are listed as follows:

1. Designing and evaluating a new fragmented IPv6 packet header compression scheme called S&SFHC. The scheme compresses the header of the second and subsequent fragments regardless of header compression of the first fragment. The S&SFHC outperforms the LOWPAN_IPHC/NHC techniques in terms of packet delivery ratio, average delay, throughput and average energy consumption.

2. Developing the S&SFHC scheme to support two operation modes; standalone and integrated. Hence, the scheme can either work as a standalone or integrated with other header compression techniques. The integrated mode shows better performance than the standalone one under the studied performance metrics.

3. Designing, implementing and evaluating the ROE2E-ABE, a cross-layer and hybrid route-over routing protocol with end-to-end fragmentation and reassembly using adaptive backoff exponents. In this protocol, the adaptive backoff is performed based on a derived formula that considers the two main collision factors; number of fragments and number of hops between the source and destination. The designed route-over routing protocol inherits both the high average packet delivery ratio of conventional route-over routing protocol and low average end-to-end delay of enhanced route-over routing protocol. The ROE2E-ABE shows better performance compared to both conventional and enhanced route-over routing protocol in terms of packet delivery ratio, average end-to-end delay, total throughput and average energy consumption.

4. Integrating the ROE2E-ABE with S&SFHC scheme and evaluating their integration overall performance based on the given performance metrics. ROE2E-ABE utilizes the developed S&SFHC scheme over multi hops scenario while maintaining end-to-end fragmentation and reassembly.

5. Analyzing the ROE2E-ABE and both conventional and enhanced route-over routing protocols in terms of average packet delivery ratio, average end-to-end delay and average energy consumption.

1.6 Thesis Organization

This thesis is organized in five chapters. Chapter 1 introduces background information on the subject area. The problem statement that motivated our research is presented before introducing the research aim and objectives. Then, it illustrates the thesis scope. Finally, the main contributions of the research are highlighted at the end of this chapter.

Chapter 2 provides a literature review of both 6LoWPAN header compression techniques and routing protocols. The chapter discusses the existing header compression techniques and then the existing related routing protocol for 6LoWPAN network are explained and discussed.

Chapter 3 elaborates on the design methodology of the proposed S&SFHC header compression scheme and its modes of operation. In addition, the chapter discusses the ROE2E-ABE routing protocol design. The relationship between the MinBE and both number of fragments and number of hops between the originator source and the final destination is derived. The cross-layer design between the adaptation and Media Access Control (MAC) layers to design a hybrid routing protocol with end-to-end fragmentation and reassembly is presented. The protocol can maintain high packet delivery ratio and low average end-to-end delay.

Chapter 4 highlights the scenarios, system configurations and simulation parameters. It presents the analysis and subsequent results of the S&SFHC scheme in both standalone and integrated modes. It also presents the performance of the ROE2E-ABE. After that, the results for the integration between ROE2E-ABE and S&SFHC are presented. Finally, the proposed ROE2E-ABE and existing conventional and enhanced route-over routing protocols are mathematically analyzed based on the performance metrics.

Finally, chapter 5 concludes the entire work done in this thesis. The recommendations for future work are presented as well.

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