Synchronized Multi-Hop Protocol for Improving the Throughput of Linear Multi-Hop Wireless Networks

（マルチホップ無線ネットワークの情報転送スループットを改善するための同期転送プロトコル）

A Thesis in
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Abstract

A multi-hop wireless network is considered promising for the next-generation communication systems because of its wide applicability to hard-to-wire circumstances. However, the throughput of a multi-hop wireless network based on the widely accepted IEEE 802.11 Standards is so low due to the inter-flow and intra-flow collisions that further applications of the network are limited. To solve this problem, Synchronized Multi-Hop Protocol has been proposed in previous papers by me, in which the IEEE 802.11 Distributed Coordination Function (DCF) is modified slightly. The protocol has been proved to keep high throughput in practical cases where there are transmission failures and large interference ranges. The protocol is also applied to the environment where the transmission rate of data packets is time-variable and may be different from node to node. It is shown that, this protocol is capable of providing high and stable throughput even if the link length, transmission rate and data packet size are variable.

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Chapter 1

INTRODUCTION

1.1 Motivation

Multi-hop wireless networks use 2 or more wireless hops to convey data packets from a source node to a destination node. A multi-hop wireless network is composed of more than three nodes equipped with wireless devices. Some of its characteristics include self-organized autonomous routing and easy-connection in hard-to-wire area.

There are two distinct applications of multi-hop wireless network, one is the commercial applications as long hop wireless sensor networks in environmental/earth monitoring field, and another is the military applications for emergency communication. It is considered promising for the next-generation communication systems because of its wide applicability to hard-to-wire circumstances.

However, the throughput of a multi-hop wireless network based on the widely accepted IEEE 802.11 Standards is so low due to inter-flow and intra-flow collisions that further applications of the network are limited. Generally, the widely-accepted IEEE 802.11 Medium Access Control (MAC) protocol [1] is being applied to a multi -hop wireless network. Although the bearer transmission rates of IEEE 802.11 family are rather high, the actual throughput in IEEE 802.11 based multi-hop wireless networks are still low. This is because the IEEE 802.11 Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism is principally designed to reduce the collision probability among multiple stations accessing the same medium, taking little account of multi-hop wireless network scenario.

A lot of papers have proposed and discussed about improved MAC protocols for solving the exposed terminal problem [2-6] and hidden terminal problem [7-8] in order to improve the throughput. Though there still exists a large gap between the theoretical upper limit of the multi-hop wireless network and actual throughputs obtained by these protocols, there seems to be no research clarifying further analysis for this throughput deterioration problem.

To solve this problem, we propose a protocol called Synchronized Multi-Hop Protocol in this research, in which the IEEE 802.11 DCF is modified slightly. The protocol has been proved to keep high throughput in practical cases where there are transmission failures and large interference ranges. Meanwhile, the protocol is also able to be applied to the environment where the transmission rate of data packets is time-variable and may be different from node to node.

1.2 Structure of Following Chapters

We first develop the necessary background theory in Chapter 2. Chapter 3 deals with the throughput deterioration problem of multi-hop wireless networks when the transmission rate is fixed. Chapter 4 presents the extended version of the proposal, showing robust throughput under multi-hop wireless networks with time-variable transmission rates from node to node. Conclusions are presented in Chapter 5 and future work is presented in Chapter 6.

Chapter 2

THEORETICAL BACKGROUND

2.1 IEEE 802.11 MAC Protocols

2.1.1 IEEE 802.11 Distribution Control Function (DCF)

In order to avoid frequent transmission failures and collision in a multi-hop wireless network, the IEEE 802.11 Standards are often implemented as a MAC layer protocol. Especially, because IEEE 802.11g MAC layer protocol is considered the most widely used one, it is applied as the MAC layer protocol in my research.
The fundamental idea of IEEE 802.11g MAC layer protocol is a DCF known as CSMA/CA. The CSMA/CA mechanism is designed to reduce the collision probability between multiple nodes in the same channel. For any node of the network, it cannot attempt to transmit any packet unless it has ensured that the medium is idle for the required duration. After determining that the medium is idle, the node will firstly transmit short control frames RTS(Request-To-Send) and CTS(Clear-To-Send) before the data packet is sent. Also, after the receiving node successfully receives the data packet, it is required to respond with an acknowledgement, called ACK frame.
According to [1], a long training structure called physical layer convergence procedure (PLCP) is included in each RTS, CTS, data packet and also ACK. The PLCP preamble is 144bits, as well as a PLCP header of 48 bits, in total, there are 192 bits of PLCP frame in each RTS, CTS, data packet and also ACK. These PLCP frames are transmitted at the lowest basic rate in case of the worst communication

environment.

On the other hand, there are time intervals between frames. They are called interframe space (IFS) in general. The IFS which is prior to transmissions of a CTS frame, an ACK frame and the data transmission is called short interframe space (SIFS), in IEEE both 802.11g and b protocols, it is equal to 0.01ms. The IFS which is prior to an RTS frame is called DCF interframe space (DIFS). In IEEE 802.11g protocol, DIFS is equal to 0.028ms, while in IEEE 802.11b protocol, DIFS is equal to 0.05ms.

$$\mathrm{DIFS} = \mathrm{Timeslot} * 2 + \mathrm{SIFS} \tag{2.1}$$

However, if there's error contained in the previous transmission, instead of DIFS, the node will wait for an extended interframe space (EIFS) before the new transmission starts. EIFS is equal to

$$\mathrm{EIFS} = \mathrm{SIFS} + \mathrm{DIFS} + \mathrm{T\_ACKatPLCPrate} \tag{2.2}$$

Another important mechanism of CSMA/CA is called random backoff time. After a DIFS or EIFS, the node shall defer a random backoff period before generating the next transmission. The backoff time is equal to

$$backoff\ timer = \mathrm{randomfunction}() * \mathrm{slottime} \tag{2.3}$$

in which the random function outputs a number which is belong to a uniform distribution of interval [0, CW]. Furthermore, everytime if an error or transmission failure is detected by the node, the contention window (CW) shall increase to the next value shown by Fig. 2.2.

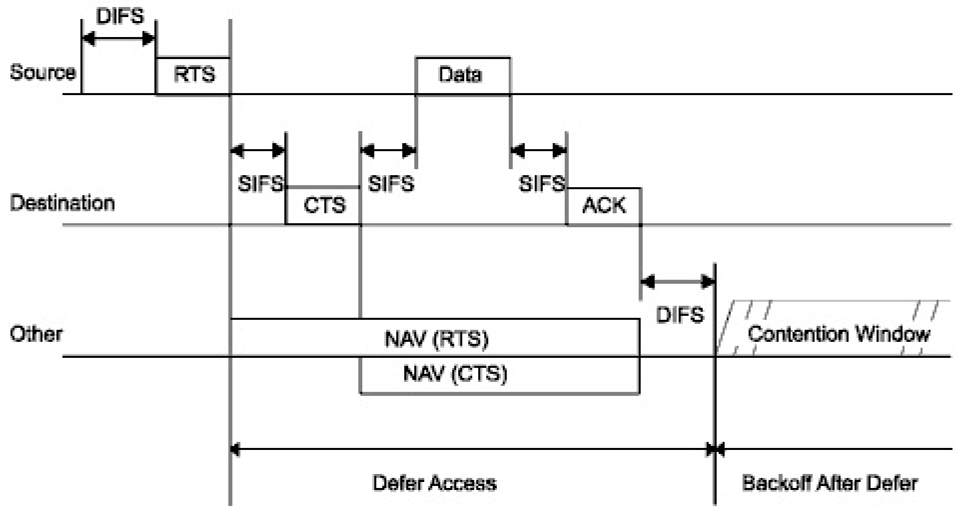


Figure 2.1. CSMA/CA of IEEE 802.11 DCF

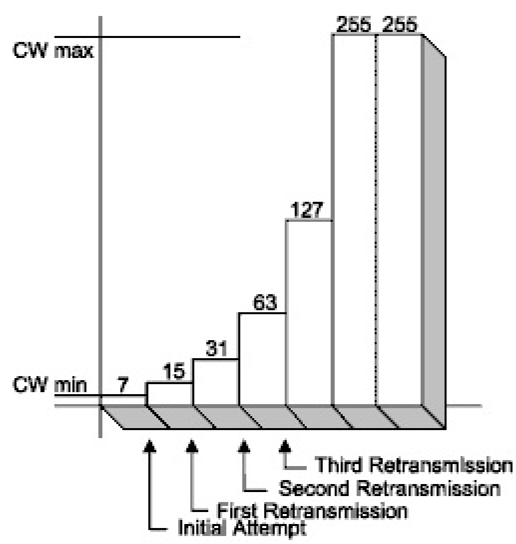


Figure 2.2. the Values of CW in Backoff Mechanism

2.1.2 IEEE 802.11b and g MAC Layer Protocols

Though IEEE 802.11b is considered an outdated wireless network protocol, for comparison in later simulations, its parameters are briefly introduced in Table 2.1.

IEEE 802.11g is designed to take the place of IEEE 802.11b Standard in 2.4GHz wireless communication channel. It provides a maximum transmission rate of 54Mbps, but also accepts 48, 36, 24, 18, 12, 9, 6 Mbps when the environment is not optimal.

IEEE 802.11g is fully compatible with IEEE 802.11b, as a result, our research, which is designed under IEEE 802.11g Standard, can also be applied in IEEE 802.11b environment if necessary.

Other parameters of IEEE 802.11g MAC layer protocol which is important to our research are listed in Table 2.2

Table 2.1. Parameters of IEEE 802.11b MAC Layer Protocol

Parameters	**Value**
SIFS	0.01ms
DIFS	0.05ms
EIFS	0.364ms
Slot Time	0.01ms
PLCP Rate	1Mbps
Basic Rate	2Mbps

Table 2.2. Parameters of IEEE 802.11g MAC Layer Protocol

Parameters	**Value**
SIFS	0.01ms
DIFS	0.028ms
EIFS	0.342ms
Slot Time	0.009ms
PLCP Rate	1Mbps
Basic Rate	4Mbps

2.2 Throughput Deterioration Problem

2.2.1 Upper Limit of Throughput

In order to avoid the hidden terminal (HT) problem [9] on a multi-hop path, IEEE 802.11 DCF is designed to prevent simultaneous transmissions between every 2 neighboring node pairs. For example, Fig. 2.3 shows a path of 5 nodes, where Node 0 and Node 2 cannot sense each other, causing a serious collision between the transmissions generated by these two nodes. Therefore, RTS/CTS handshake is introduced in IEEE 802.11 DCF to solve this HT problem. This study leads to the fact that only node pairs which are three or more hop away from each other can make transmissions simultaneously (e.g. Node 0 and Node 1 pair can communicate with each other without any collision even if Node 3 is communicating with Node 4). In other words, the maximum throughput of a three- or more- hop network is theoretically 1/3 that of a single-hop network. The theoretical upper limit of a 2 hop network is 1/2 that of one hop network, since only one of the two hops in the network can be used for transmission at a time.

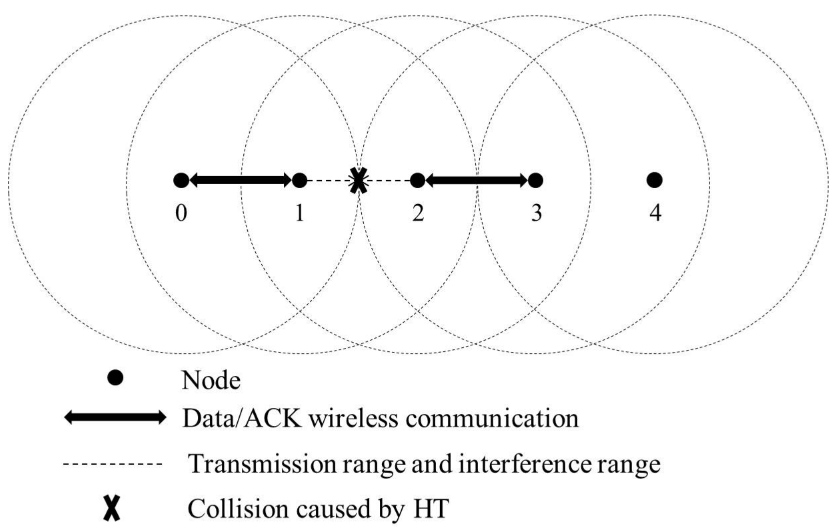


Figure 2.3. Hidden Terminal Problem That Disables Simultaneous Transmissions Between the 1st Hop and the 3rd Hop

2.2.2 Description of the Simulation Environment

For the purpose of demonstrating the efficiency of our proposal and comparing it with some existing methods in the following chapters, simulation experiments have been conducted under IEEE 802.11b or g environment by Network Simulator (NS) 2.34[10].

In terms of the debugging tool, gdb under Ubuntu 12.04 is utilized. In order to apply gdb debugger to debug Network Simulator, following configurations are necessary.

Firstly, following command is used for install gdb in Ubuntu.

#sudo apt-get install gdb

Then, the makefile in /ns-allinone-2.34/ns-2.34 are modified as follows,

replacing line 55 "*CCOPT = -Wall*" with "*CCOPT = -g -Wall*",*i.e.* add "*-g*" after "*CCOPT=*".

Finally, by re-compiling NS, the debugger should be successfully installed. The re-compiling commands are,

#sudo make clean

#sudo make depend

#sudo make

Noting that, there might be some errors when executing "*make depend*", but just ignore it.

Some necessary commands to debug NS in gdb debugger are:

To enter the gdb debugger by

gdb ns at /ns-allinone-2.34/ns-2.34

Setting breakpoint by

b filename:line

Running tcl program by

r filename

More useful commands can be found in [11].

IEEE 802.11g simulation parameters with their values are given in Table 2.3. If the IEEE 802.11b environment is simulated, just use the corresponding parameters in Table 2.1 to replace those of Table 2.3. The network topology is linear, where all the nodes are placed in a line with the same distance d of 100m between every two neighboring nodes. The packet size is firstly set to 1500bytes because this is the recommended packet size for wireless communication. Later experiments may adjust the data packet size to show further characteristics of the proposals. These parameters ensure that every two neighboring nodes are capable of direct communication with each other, but two nodes that are two or more hops apart have to communicate with each other through the relay of one or more intermediate nodes.

Table 2.3. Simulatation Parameters of IEEE 802.11g Configuration

Parameters	**Value**
Channel	1
Transport Protocol	UDP
CBR	12Mbps
Routing Protocol	AODV
Data Pcket Size	1500byte
Simulation Duration Rate	1000s
Interface Queue Size	50 Packets
Distance Between Neighboring Nodes	100m
Interference Range	150m
Transmission Range	150m
SIFS	0.01ms
DIFS	0.028ms
EIFS	0.342ms
Slot Time	0.009ms
PLCP Rate	1Mbps
Basic Rate	4Mbps
Data Rate	54Mbps

2.2.3 Throughput Deterioration in an IEEE 802.11 DCF Multi-Hop Wireless Network

Simulation parameters are set according to IEEE 802.11b environment. The network consists of (n+1) nodes, where Node 0 is the source and Node n is the destination. The configuration of the network topology is given in Fig. 2.4, where all the nodes are placed in a line with the distance of 100m between every two neighboring nodes. This topology is named linear and it ensures that every two neighboring nodes are capable of direct communication with each other. Radio propagation is based on the Two-Ray Ground reflection model.

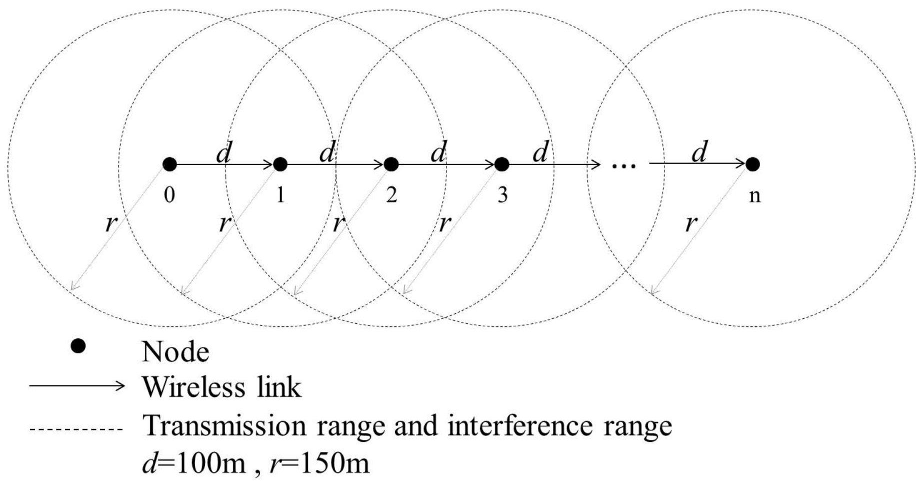


Figure 2.4. The Topology of the Simulation

Fig. 2.5 shows the simulation results on the average time cost of transmitting one data packet from the source to the destination. The time cost is elaborated into the detailed components including data frame transmission, backoff and Network Allocation Vector (NAV) intervals, collision overhead, MAC control message transmission, and routing overhead. Let $T_{\text{component}}$ denote the time cost of each component for one data packet transmission and $T_{\text{component}}$ is defined by the following equation.

$$T_{\text{component}} = \frac{\text{total time of the component}}{\text{number of received data packets}} \tag{2.4}$$

Let h denote the number of hops. If h increases, the end-to-end time cost of one data packet transmission grows rapidly as shown in Fig. 2.5. In detail, the time costs of transmitting a data frame and a set of MAC control messages for one hop are $T_{\text{data}} = 1.322$ms and $T_{\text{MAC}} = 0.848$ms respectively, and they increase just in proportion to the number of hops h .

On the other hand, the time costs of backoff and NAV intervals, and AODV overhead increase much faster. Although the time cost of collisions is very small, the existence of intra-flow collisions and the resulting time costs of backoff, NAV and AODV overhead are the main reasons why the throughput of an IEEE 802.11-based multi-hop wireless network is much smaller than its theoretical upper limit. A time sequence example of messages is shown in Fig. 2.6. In this figure, Node 2 transmits data packet DATA1 to Node 3. Then Node 0 attempts a new transmission to Node 2 as well. According to IEEE 802.11 DCF, Node 1 is blocked by the NAV in the overheard RTS generated by Node 2. Therefore, the first attempt of RTS by Node 0 fails, and this failure is followed by an exponentially increased contention window. The CW shall increase exponentially every time a failure of transmission happens. Furthermore, if the number of failures reaches Station Short Retry Count (SSRC), which is usually 7, then the concerned wireless link is considered broken and AODV will reestablish the path between the source and the destination.[1] Such extended backoff timer and AODV overhead are the most dominant cause for the throughput deterioration of an IEEE 802.11 multi-hop wireless network.

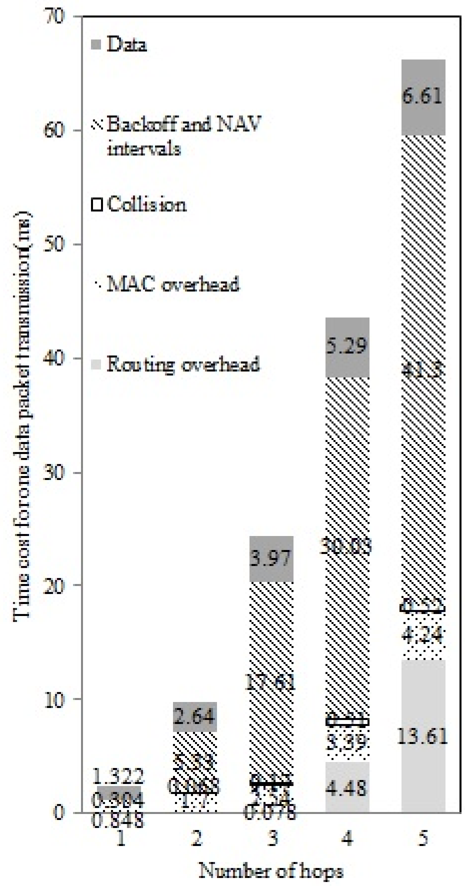


Figure 2.5. Time Cost of One Data Packet Transmission from the Source to the Destination by Conventional IEEE 802.11b DCF

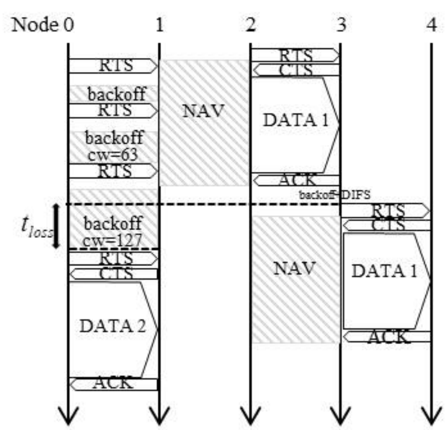


Figure 2.6. A Sequence Diagram Example of A Linear IEEE 802.11 Multi-hop Wireless Network

2.2.4 Literature Review

A multi-hop wireless network is considered promising for the next generation communication systems because of its self-organized characteristics, which enable the network to be applied in especially hard-to-wire situations. There are strong demands from commercial applications such as the "community wireless networks" [12], sensor networks [13], and military applications such as battle field communications.

Despite the promising application prospects, an actual multi-hop wireless network built under present IEEE 802.11 framework is faced with a severe throughput deterioration problem. Previous researchers have discovered that the deterioration is caused by inter- and intra-flow collisions [14-15].

MAC provides channel access control mechanism, which has a dominant effect on the throughput of the network. IEEE 802.11 RTS/CTS/DATA/ACK 4-way handshake was designed to alleviate the hidden terminal problem [16], but in practice this conventional IEEE 802.11 Standard is not sufficient for solving the throughput deterioration problem, and a lot of improved MAC protocols have been proposed. In order to solve the inter-flow collisions so as to improve the throughput performance, [17-18] proposed dual channel or even multi-channel carrier sensing MAC protocols. However such proposals require new physical layer and multi-channel hard-ware devices as well. Another important idea is spatial reuse and power control proposals [19-23]. However, power leverage introduces asymmetric links [24] so that the range of application of these protocols is restricted. Besides, power control mechanisms also require physical layer modification and coordination. Tuning the carrier sensing threshold is also a popular research topic [25-28]. These protocols tried to make a trade-off between preventing hidden terminal collisions and permitting exposed terminal transmission. However, the effectiveness is always limited and it is not applicable to intra-flow situations.

MACA-P [29] is one of the earliest and most famous protocols for solving the exposed terminal problem in an IEEE 802.11 multi-hop wireless network. Alleviating the exposed terminal problem is helpful for avoiding inter-flow collisions. However, it is not a suitable solution for intra-flow collisions of a multi-hop wireless network. Therefore, the improvement of the throughput by MACA-P is very limited.

Recently, [30] proposed a MAC protocol called EMAC, which has been designed for solving the intra-flow collisions of a multi-hop wireless network. It has abolished the RTS/CTS handshake, and instead, it has introduced a new control message called PION to coordinate all the nodes on the given path from a source node to a destination node. Only a little after the source transmitted the PION message and confirmed that the downstream node received the PION, the source starts the data transmission. However, [30] does not show the timings of the transmission of the following PIONs and data packets after the first complete relay of the first data packet. According to some simulation results in [30], the throughput of a path with three or more hops is a little more than 1/4 that of one hop path. As shown in Chapter 2.2.1, the theoretical upper limit of the throughput of a path with three or more hops is 1/3 that of one hop path. That is, although EMAC has improved the throughput of a multi-hop network, the throughput of EMAC is well below the theoretical upper limit.

Also recently, [31] proposed a protocol called RB-MAC, designed for eliminating the intra-flow collisions with the following strategies. First, a source node of a flow competes with other source nodes to get the channel for the whole path starting with the first source. Second, the relay nodes along the path occupy the channel until all the packets reach the destination in such a manner that the nodes forward the packets immediately after receiving the packets. This protocol seems effective. However, there can be transmission collision between an RTS message and a data packet or another control message and there can be transmission failure of data packet due to some noise or interference in the channel, which makes the throughput performance of RB-MAC soon retrogress to that of the conventional IEEE 802.11 DCF, and the throughput deteriorates significantly, since RB-MAC has no counteractions against such transmission failure.

Accordingly, none of the existing MAC protocols are considered to be sufficient to achieve the throughput that is close enough to the theoretical upper limit.

Thus the purpose of this paper is to propose a new MAC protocol which can improve the throughput performance of an IEEE 802.11 multi-hop wireless network to the level that is very close to its theoretical upper limit of 1/3 that of the single-hop network by a minimal modification to the original standard.

Chapter 3

Synchronized Multi-Hop Protocol in Fixed Rate Networks

3.1 Proposal of Synchronized Multi-Hop Protocol (SMHP)

3.1.1 Proposal of Synchronized Multi-Hop Protocol (SMHP)

In Fig. 2.6, if we can come up with a means of notifying Node 0 of the ongoing transmission between Node 2 and Node 3, then the useless backoff extension and AODV overhead can be eliminated. Furthermore,t_{loss} in Fig. 2.6, which is the time difference between the RTS transmission of Node 0 and that of Node 3, can be eliminated so that the data transmission of Node 0 and that of Node 3 can be synchronized to improve the transmission efficiency of the network to a larger extent.

We propose a MAC protocol to achieve the improvement of the transmission efficiency by minimal modification of the original standard [32,33]. The proposal is called SMHP (Synchronized Multi-Hop Protocol) hereinafter and its two main principles are described below. Except for the modifications based on these principles, the protocol is in accordance with the mechanisms of the conventional IEEE 802.11 Standard.

Principle 1:

If the 2nd node (Node 1 in Fig. 3.1) from the source in the path overhears an RTS message generated by its downstream node (Node 2), this overhearing node sends a newly defined control message named S_CTS back to its upstream neighbor node (Node 0), in order to inform Node 0 of the ongoing transmission happening 2 hop away (transmission from Node 2 to Node 3). Then Node 0 becomes able to access the channel again after the NAV in S_CTS message expires, where the expiring time of this NAV is the same as that of the NAV in the RTS overheard by Node 1.

Principle 2:

The backoff timer of a node is set to zero if the node has just received a data frame successfully and also if the node has just recovered from the NAV of S_CTS.

Principle 1 is designed for realizing the synchronized transmission between every two nodes three-hop away. Above all, the objective is to come up with a means to notify Node 0 in Fig. 3.1 of the ongoing transmission at Node 2, so that no useless RTS attempt and extended backoff will be generated at Node 0. The duration information of data transmission by Node 2 is stored in RTS frame as NAV, and the RTS frame is overheard by Node 1 to generate NAV interval which can be forwarded in S_CTS message from Node 1 to Node 0.

Principle 2 is designed for eliminating unnecessary waiting. Generally, the objective of backoff mechanism is to set random waiting time for different nodes in order to resolve the medium contention conflicts. However, since the synchronization mechanism realized by SMHP has already solved the contention problem, the backoff timers of the synchronized node pairs are set to zero without leading to any channel conflict. Thus, the extension of backoff timer is avoided, and such saved time contributes to the synchronization mechanism of Principle 1 to further improve the efficiency.

S_CTS requires a longer IFS than SIFS at a node (Node 1 in Fig. 3.1) in order to avoid collision at its downstream node (Node 2) with the ongoing reception of a message (e.g. CTS received at Node 2). The IFS of S_CTS $\mathrm{S_{SIFS}}$ is defined as follows.

$$\mathrm{S_{SIFS}} = \mathrm{SIFS} + T_{\mathrm{CTS}} + \mathrm{SIFS} \tag{3.1}$$

$$\mathrm{NAV_{S_{CTS}}} = \mathrm{NAV_{RTS}} - \mathrm{S_{SIFS}} - T_{\mathrm{S_{CTS}}} \tag{3.2}$$

where T_{CTS} and $T_{\mathrm{S_{CTS}}}$ denote the time intervals required for the transmission of CTS and S_CTS, respectively, and $\mathrm{NAV_{RTS}}$ and $\mathrm{NAV_{S_{CTS}}}$ denote the NAV duration information stored in RTS and S_CTS messages, respectively.

Principles 1 and 2 are called S_CTS Mechanism (SM) and Prioritized Backoff (PB) hereinafter, respectively.

It should be noted that the first half of Principle 2 is the same as the principle of RB-MAC in terms of relaying the data packets immediately along the path. However, the latter half of Principle 2 regulates nodes after the expiry of $\mathrm{NAV_{S_{CTS}}}$ to start to transmit RTS immediately, which is an important function coordinating with SM for successful synchronization. Such coordination of Principles 1 and 2 is the most crucial reason for large throughput improvement of SMHP.

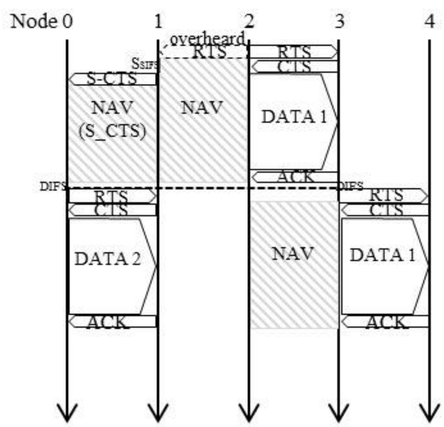


Figure 3.1. S_CTS Mechanism

3.1.2 Evaluation Results and Discussions

Fig. 3.2(a) shows the end-to-end throughput of theoretical upper limit, proposed SMHP with PB, proposed SMHP without PB, RB-MAC and IEEE 802.11 DCF under IEEE 802.11b environment. The simulation parameters and their values are the same as those in Table 2.1. The topology is the same as that shown in Fig. 2.4.

The end-to-end throughput $\mathrm{Throughput_{end-to-end}}$ in Fig. 3.2(a) is calculated as the total number of received data packets at destination node divided by the simulation duration. That is,

$$\text{Throughput}_{\text{end-to-end}} = \frac{N_{\text{pkt}} \times S_{\text{pkt}}}{T_{\text{simulation}}} \tag{3.3}$$

where N_{pkt} denotes the total number of received data packets at the destination, S_{pkt} denotes the size of the data frame, $T_{\text{simulation}}$ denotes the simulation duration. Given the data rate of 11Mbps and data packet size of 1500byte, the line with square marks in Fig. 3.2(a) shows the theoretical upper limit of the throughput a multi-hop wireless network can achieve supposing no backoff timer, IFSs or collisions.

Therefore, the upper limit for 1-hop wireless network is about 5.8Mbps, by replacing the N_{pkt} in Eq (3.4) with N_{upper}, where

$$N_{\text{upper}} = \frac{T_{\text{simulation}}}{T_{\text{simulation}} + T_{\text{CTS}} + T_{\text{DATA}} + T_{\text{ACK}}} \tag{3.4}$$

$$\text{upper\_limit}_{\text{h=1}} = \frac{N_{\max} \times S_{\text{pkt}}}{T_{\text{simulation}}} \tag{3.5}$$

and $\text{upper\_limit}_{h=i}$ denotes the theoretical upper limit of the throughput of i-hop wireless network.

As shown in Eq (3.4) and Eq (3.5), 2-hop wireless network can achieve at most half of the throughput of a one hop network. According to Chapter 2.2.1, the upper limit for a multi-hop wireless network, when h>2, is one third that of a single hop wireless network.

$$\text{upper\_limit}_{\text{h=2}} = \frac{1}{2} \times \frac{N_{\max} \times S_{\text{pkt}}}{T_{\text{simulation}}} \tag{3.6}$$

$$\text{upper\_limit}_{\text{h=3}} = \frac{1}{3} \times \frac{N_{\max} \times S_{\text{pkt}}}{T_{\text{simulation}}} \tag{3.7}$$

Due to extended backoff timers, collisions and redundant AODV overhead caused by retransmission as shown in Chapter 2.2.3, the throughput of conventional IEEE 802.11b DCF in MAC layer is always the lowest and is characterized by its decrease along with the increase in the number of hops as shown by the line with cross marks in Fig. 3.2(a).

The throughput of SMHP is shown elaborately in the same figure. The line with dot marks shows the SMHP performance without PB, where the backoff timer is fixed to the average value of the backoff timers in the conventional IEEE 802.11

Standard. It should be noted that SMHP without PB adopts only Principle 1, i.e. SM. This line demonstrates the effectiveness of sole SM.

Noting that, the backoff timers for SMHP without PB are made to 0.2ms in IEEE 802.11b environment, and 0.09ms in IEEE 802.11g environment. It is set to these values because they are equal to the average value of backoff mechanism. The proof is shown below.

Firstly, when one node finishes the transmission to its downstream node, both of these 2 nodes will start backoff timer countdown. The one with smaller backoff will take the chance to transmit the packet in its queue in the first place. Therefore, the average value of backoff timers is calculated as the following statements.

If we draw n numbers which are uniformly distributed between 0 and k , then the probability distribution of the minimum number among these n numbers, denoted as u, will be a beta distribution.

$$u_1 \ (1, n) \tag{3.8}$$

and the mean of the beta distribution is

$$\text{mean}_{u_1} = \frac{k}{1+n} \tag{3.9}$$

Proof

Since initial_CW=31, slot time=0.02ms in IEEE 802.11b and slot time=0.009ms in IEEE 802.11g Standard. Let's suppose that node A is transmitting to node B, t_1 is a random backoff timer for node A after transmission, and t_2 is a random backoff timer for node B, we know that the actual waiting time between 2 transmissions will be $c = \min(t_1, t_2)$

Because t_1 and t_2 are uniformly distributed, the probability distribution of c will be a beta distribution[34], and the mean of the beta distribution equals,

$$\text{mean}_c = \text{cw} \times \text{Slottime} \times \frac{1}{1+n} \tag{3.10}$$

where $n = 2$, Therefore, the mean value of c is approximately 0.2ms in IEEE 802.11b environment, and 0.09ms in IEEE 802.11g environment.

In general, both SMHP with PB and SMHP without PB, which are shown by the lines with triangle and dot marks in the figure, respectively, outperform RB-MAC, which is shown by the line with asterisks. For an example, in the 5-hop topology network in Fig. 3.2(a), RB-MAC can improve the throughput by 72% compared with the conventional IEEE 802.11b Standard, while SMHP without PB can improve by 86%, and SMHP with PB can improve by 103%.

This result shows that, though RB-MAC manages to improve the throughput by making good use of the channel and relaying the data continuously, our proposed SMHP with only S_CTS mechanism still outperforms RB-MAC when the number of hops is three or more. This is because S_CTS enables node pairs which are three-hop away from each other to transmit in a synchronized manner without causing any collisions, and this SM plays a more important role than PB mechanism for achieving high throughput.

Furthermore, since SM is capable of launching synchronized transmission and completely avoiding collisions, the gap between the theoretical upper limit and SMHP in Fig. 3.2 is just because of various IFSs and backoff timers. Since in reality it is necessary to place time intervals between frames to provide different priority levels, we assert that SMHP is the optimized MAC protocol which is closest to the upper limit.

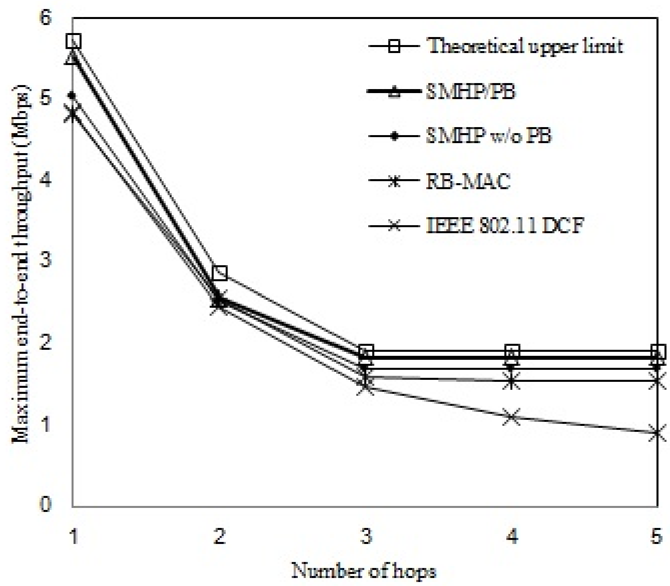
Fig. 3.2(b) shows the end-to-end throughputs of these MAC protocols under IEEE 802.11g environment. The simulation parameters and their values for IEEE 802.11g environment are shown in Table 2.3. CBR, MAC layer data rate, basic rate, slot time, SIFS and DIFS are different from those in IEEE 802.11b scenario.

Given the data rate of 54Mbps, the throughput of IEEE 802.11g DCF MAC protocol has improved greatly as well in comparison with that of IEEE 802.11b DCF MAC protocol, therefore the advantages of SMHP and RB-MAC are not as large as in IEEE 802.11b environment, but SMHP still outperforms RB-MAC in all the situations. In 5-hop topology for example, RB-MAC has improved the throughput of the conventional method by 57%, while SMHP without PB has improved by 70% and SMHP with PB has improved by 84%.

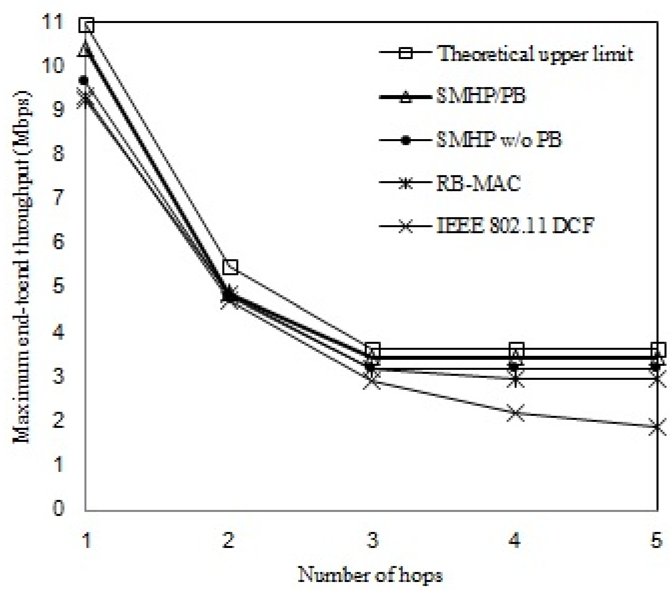
Based on the analysis of this subsection, we conclude that the performance of SMHP outperforms that of RB-MAC, and average end-to-end SMHP with PB is very close to its theoretical upper limit of 1/3 that of the single-hop network, we assert SMHP as the best MAC protocol compared with RB-MAC, EMAC, MACA-P and conventional IEEE 802.11 DCF.

Fig. 3.3 shows the time cost of transmitting one data packet from the source to destination by SMHP without PB, for the purpose of clarifying the efficiency and improvement realized by SM more elaborately.

The scenario parameters are the same as those in Table 2.1. And equivalent counterparts to the elements in Fig. 2.5 are illustrated in Fig. 3.3, including time costs of data frames, backoff and NAV intervals, MAC overhead and routing overhead.



(a) IEEE 802.11b configuration



(b) IEEE 802.11g configuration

Figure 3.2. Throughput Comparison

Fig. 3.3 is to demonstrate the efficiency and throughput improvement realized by S_CTS mechanism. As is observed in this figure, the backoff and NAV intervals are reduced greatly and AODV overhead is eliminated completely by SM. In other words, it is confirmed that these are the main reasons for the high throughput achieved by SMHP, which is very close to the theoretical upper limit of a multi-hop wireless network.

Compared to Fig. 2.5, the average time cost of transmitting one data packet from the source to the destination in Fig. 3.3 is reduced significantly by SM when h>3. For example, in 5-hop topology, the time cost is reduced from 66.28ms to 35.11ms, which means 47% of the total cost is reduced. This is because of the synchronized transmissions when h>3. It should be noted that PB is still not applied in this figure, yet the advantage of SM is still prominent.

While the time costs of data transmission and MAC control messages of SMHP without PB are basically equivalent to those in IEEE 802.11b DCF, with the help of SM, time cost of collisions, and routing overhead are removed completely. On the other hand, extended backoff timers and NAV intervals are reduced significantly. This is because synchronized transmission is introduced and inter-flow collisions are avoided by SM, so that there is no transmission failure or increased CW size, and therefore the end-to-end throughput of the network can be improved prominently. Furthermore, the longer the path length is, the more backoff and NAV can be saved by SM, and thus the throughput improvement by SMHP without PB will keep growing larger when the number of hops increases.

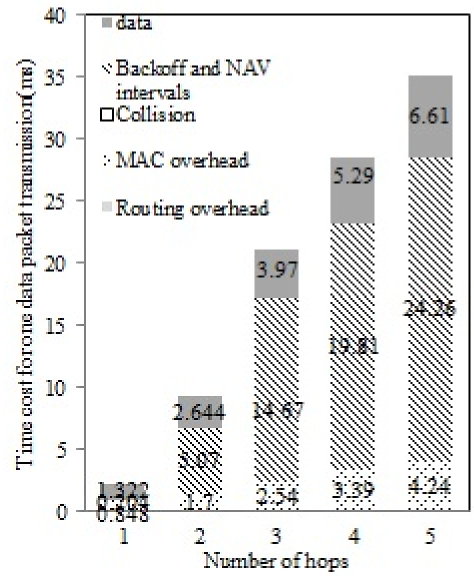


Figure 3.3. Time Cost of One Data Packet Transmission from the Source to the Destination by SMHP w/o PB

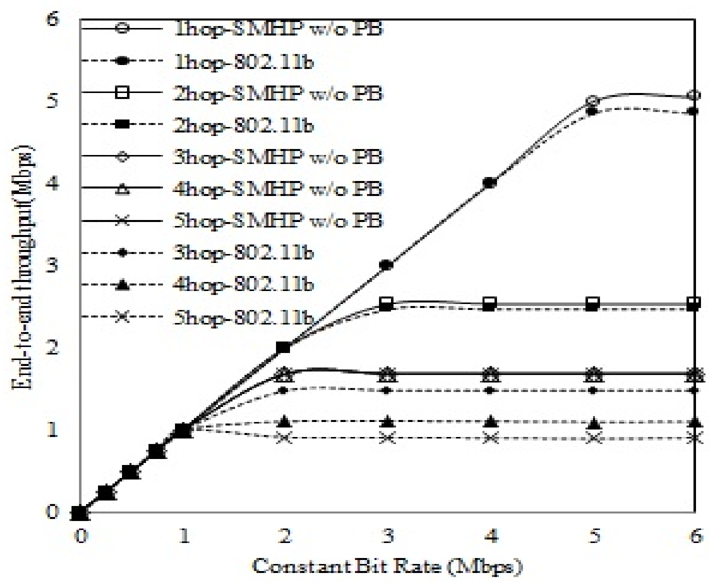
Fig. 3.4(a) shows the throughput of SMHP without PB under IEEE 802.11b environment over a variety of CBR and path lengths. Given the data rate of 11Mbps in IEEE 802.11b configuration, the simulations are conducted according to the parameters in Table 2.1.

Fig. 3.4(b) shows the throughput performance of complete SMHP with PB under IEEE 802.11g environment, and the simulation parameters are the same as those in Table 2.3.

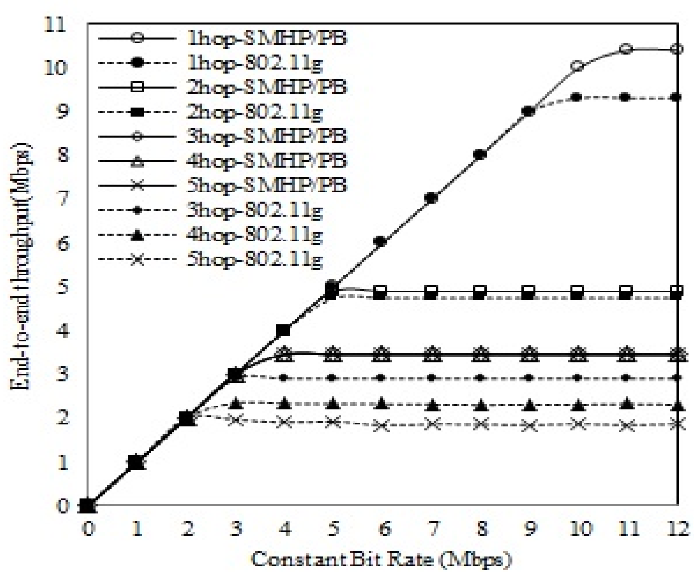
These two figures show that SMHP keeps the advantage over IEEE 802.11 DCF regardless of packet generation rate and path length.

Another fact is that when h>2, the throughput of SMHP will keep the same regardless of the path length. This is because when h>2, SMHP can preserve synchronized transmission among node pairs every 3-hop away, making the throughput stable and close to the upper limit, i.e. 1/3 of the throughput in single-hop wireless network.

And the effect of packet generation rate to the throughput performance is expressed in the way that, when CBR is smaller than the throughput of Fig. 3.2, the output of actual throughput is determined by the value of CBR. And this fact applies to all MAC protocols.



(a) IEEE 802.11b SMHP w/o PB VS. IEEE 802.11b DCF



(b) IEEE 802.11g SMHP/PB VS. IEEE 802.11g DCF

Figure 3.4. End-to-end Throughput VS. Different CBRs and Different Path Lengths

3.2 Extension of SMHP against Transmission Failures

3.2.1 The Extended SMHP against Transmission Failures

Transmission of a message may fail when there exists inter-flow and intra-flow collision or noise in the channel. According to IEEE 802.11 Standards, the network should be able to stand with the environment with Bit Error Rate (BER) of 10^{-5}, namely the Packet Error Rate (PER) of around 0.1 [1], which means all the possible MAC protocols should be resistant to the packet error and transmission failure.

The proposed SMHP is not only successful in solving the intra-flow collision as stated in Chapter 2.2.4, but it is also capable of preserving the throughput in situations of low communication quality by the following proposed fast recovery mechanism.

Such a proposal for fast transmission failure recovery has not been published before, and thus our proposal for the fast recovery in SMHP is considered to possess high originality.

As shown in Fig. 3.5, the principle of the recovery is to force a node, in which a data transmission failure is detected (e.g. Node 3 in Fig. 3.5), to retransmit the failed frame as immediately as possible after the detection, where the detection is made by no reception of ACK from Node 4 by Node 3 before the timer of ACK interval expires. And nodes which are faced with RTS transmission failure (e.g. Node 1) due to the collision of this RTS and some frame related to the above data retransmission, retransmits after pre-estimated period T_e. By this principle, the loss time due to the transmission failure becomes minimum as shown in Fig.3.5. T_e is calculated by the equation below when the data generation at the source node and the packet size is constant.

$$T_e = \text{SIFS} + T_{\text{DATA}} + \text{DIFS} + T_{\text{ACK}} \tag{3.11}$$

where T_{DATA} denotes the time for one data frame transmission, T_{ACK} denotes the time for one ACK frame transmission.

As a result, each node is delayed only by one T_{SMHP} due to the transmission failure, where T_{SMHP} denotes the time required for one complete data frame transmission by RTS/CTS/DATA/ACK 4-Way handshake in SMHP and T_{SMHP} is as shown below.

$$T_{\text{SMHP}} = T_{\text{RTS}} + T_{\text{CTS}} + T_{\text{DATA}} + T_{\text{ACK}} + 3\text{SIFS} + \text{DIFS} \tag{3.12}$$

In the conventional IEEE 802.11 Standards, such a transmission failure will lead to the increase in the contention window size resulting in a serious throughput deterioration problem, since the total loss time will be much greater than T_{SMHP}.

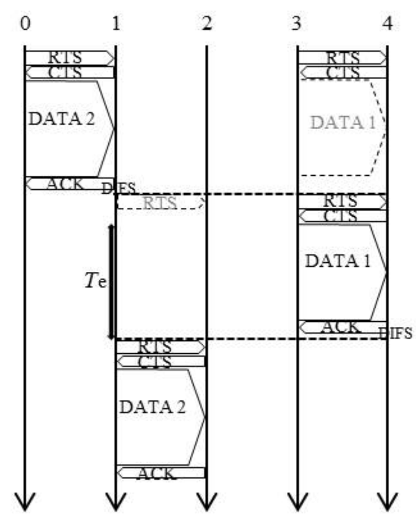


Figure 3.5. The Sequence Diagram of the Fast Recovery Mechanism of Extended SMHP

3.2.2 Evaluation Results and Discussions

Fig. 3.6 (a) and (b) show the performance of SMHP, RB-MAC and IEEE 802.11 DCF under the Packet Error Rate of 0.1 and 0.01.

Fig. 3.6(a) is evaluated under IEEE 802.11b configuration following Table 2.1, while Fig. 3.6(b) is evaluated under IEEE 802.11g configuration following Table 2.3.

When h>2, the advantages of SMHP with PB over RB-MAC keep growing larger as h increases, regardless of PER and network configurations in terms of the number of hops. Especially when PER=0.1, the throughput of RB-MAC and conventional

IEEE 802.11 DCF deteriorate significantly as the path length grows, while the throughput of SMHP with PB remains much more stable.

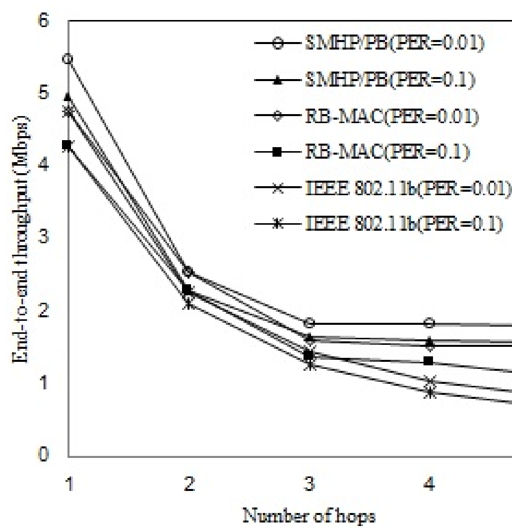
It also shows that the deterioration rate of SMHP with PB is steady regardless of the network configuration. This is because in theory, if n data frames are disturbed and retransmitted, $n \times T_{\text{SMHP}}$ are used to recover the failures, which means that the deterioration rate is only dependent on the parameter of PER. On the other hand, since there is no specific recovery mechanism in either IEEE 802.11 DCF or RB-MAC, the throughput deteriorates greatly as the PER grows.

Table 3.1. Throughput Deterioration Rate from the Ideal Scenario (PER=0) in 5-Hop IEEE 802.11b Configuration

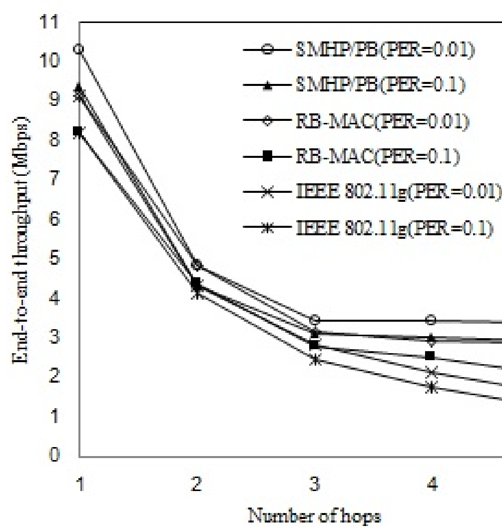
	PER=0.01	**PER=0.1**
SMHP	1.4%	14.9%
RB-MAC	3.4%	28.6%
802.11b DCF	7.7%	23.5%

Table 3.2. Throughput Deterioration Rate from the Ideal Scenario (PER=0) in 5-Hop IEEE 802.11g Configuration

	PER=0.01	**PER=0.1**
SMHP	1.4%	14.9%
RB-MAC	2.3%	30.3%
802.11b DCF	14.5%	32.7%



(a) IEEE 802.11b Configuration



(b) IEEE 802.11g Configuration

Figure 3.6. End-to-end Throughput Comparison in Scenarios with Different PERs

3.3 Extension of SMHP against Large Interference Range

3.3.1 The Extended SMHP(E-SMHP)

In practice, the transmission and the interference ranges are decided by a lot of factors including the transmission power, the receiving power threshold and the carrier sense threshold. The interference range is usually around 2 times larger than the transmission range [35].

SMHP is capable of providing stable synchronized transmission when the interference range is smaller than $2d$, where d is the distance between any two neighboring nodes in the path. However, if the interference range is larger than $2d$, S_CTS may collide with some on-going transmissions in its interference range. Therefore, the following counteraction is proposed to solve the problem as another extension to SMHP.

When the interference range $R_{\mathrm{ir}} > 2d$, the S_CTS mechanism is disabled by E-SMHP, and the synchronized transmission will be launched after an EIFS interval as shown in Fig. 3.7. The synchronization can be maintained without S_CTS mechanism under the large interference range because the carrier sensing is extended from 1-hop distance to 2-hop distance. In Fig. 3.7, such extended carrier sensing is capable of notifying node 0 of the on-going transmission between nodes 2 and 3, for the reason that the EIFS interval is equal to the time for transmitting an ACK frame at the lowest rate of the network.

Furthermore, because of the large interference range, simultaneous RTS transmission of nodes 0 and 3 will cause a collision at Node 1 in this figure, then according to the fast recovery mechanism of SMHP, a waiting time of T_e is assigned to Node 0. The synchronization between nodes 0 and 4 is realized in the next time slot.

Since in the current condition the maximum throughput should be 1/4 of the single-hop throughput, this proposal is capable of providing a throughput very close to this upper limit. By such extensions of Chapter 3.2.1 and Chapter 3.3.1, SMHP becomes resistant in environments with the large interference range as well as transmission failures. SMHP with PB and these extensions are named Extended-SMHP (E-SMHP).

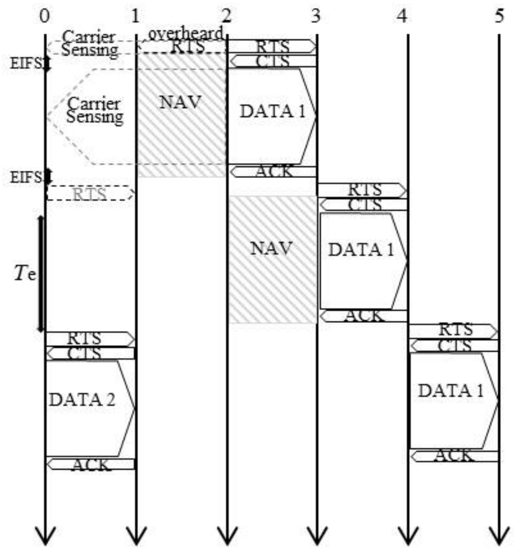


Figure 3.7. The Sequence Diagram of Extended SMHP for Large Interference Range

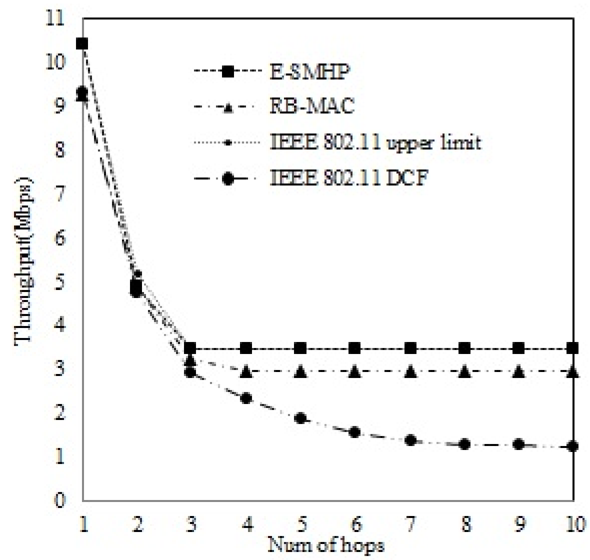
3.3.2 Evaluation Results and Discussions

The IEEE 802.11 upper limit (the line with small dots) in Fig. 3.8(a) means the theoretical maximum throughput a multi-hop wireless network can achieve supposing no backoff timers or collisions. 2-hop wireless network can achieve at most half of the throughput of a one hop network. When the number of hops is 3 or more, the upper limit is the same and equal to one third of the single-hop upper limit as achieved in Fig. 3.1. In Fig. 3.8(b), because PER=0.1, the upper limit decreases by 10%.

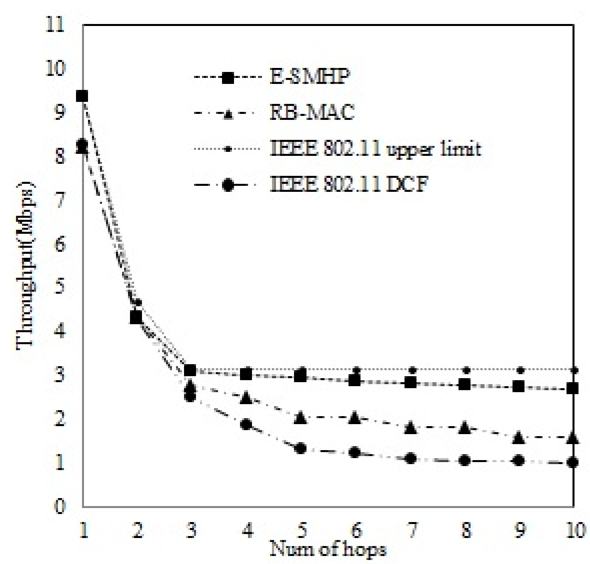
Meanwhile, due to the extended backoff timers, collisions and redundant AODV overhead caused by retransmission as shown in Fig. 2.6, the throughput of conventional IEEE 802.11 DCF is always the lowest among the four protocols and decreases if the number of hops increases.

In Fig 3.8(a), where PER=0, E-SMHP outperforms RB-MAC and DCF significantly, and the advantages grow as the number of hops increases. Furthermore, the throughput of E-SMHP is very close to the upper limit, which means the synchronization achieved by E-SMHP is the optimal solution for solving the intra-flow collisions in linear multi-hop wireless networks.

In Fig. 3.8(b). where PER=0.1, E-SMHP still keeps its advantages over RB-MAC and DCF significantly. Furthermore, the advantages will increase as the number of hops grows. Though one transmission failure causes $1T_{\mathrm{SMHP}}$ time loss over all the nodes as explained by Fig. 3.5, E-SMHP still outperforms RB-MAC and 802.11 DCF stably even if the number of hops is equal to 10. Since a multi-hop network with more than 10 hops is considered rare, it is concluded that E-SMHP is robust against the transmission failures. Meanwhile, the throughput of RB-MAC and DCF will deteriorate greatly as the number of hops or PER increases.



(a) (PER=0, $R_{\mathrm{ir}} = R_{\mathrm{tx}}$)



(b) (PER=0.1, $R_{\mathrm{ir}} = R_{\mathrm{tx}}$)

Figure 3.8. Throughput Comparison Given Different PER

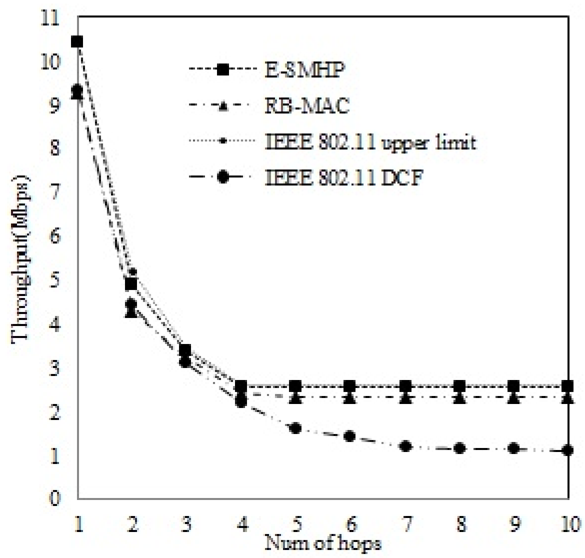
The experiments are conducted under the same IEEE 802.11g multi-hop wireless network, except that the interference range is set to 290m (d=100m, i.e.$R_{\mathrm{ir}} >$

$2d$.

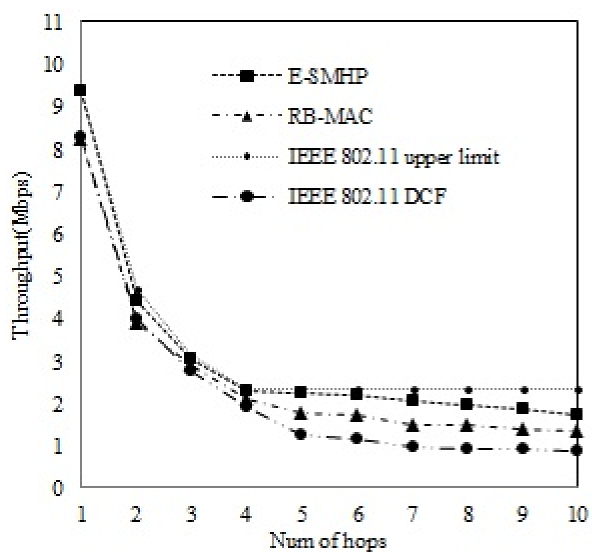
When the interference range is larger than or equal to $2d$, the upper limit of the maximum throughput for a multi-hop network will be decreased to 1/4 of the maximum single-hop throughput, and as shown in Fig. 3.7, only nodes with the distance of $4d$ can simultaneously transmit packets.

In Fig. 3.9(a), it is shown that E-SMHP is capable of providing a stable and high throughput under the large interference range by disabling the S_CTS mechanism and applying the EIFS function in the conventional IEEE 802.11 Standards as described in Chapter 3.3.1. Furthermore, the throughput of E-SMHP is very close to the upper limit whereas the throughput of RB-MAC and DCF deteriorate greatly. Thus E-SMHP has been proved optimal even in environments with large interference range.

In Fig. 3.9(b), where PER=0.1, when the number of hops equals 10, E-SMHP outperforms RB-MAC by 29.6% and outperforms DCF by 96.3%. Though the throughput of E-SMHP is affected by the large PER a little, it still possesses prominent advantages over other existing methods. Thus it is concluded that E-SMHP is the best solution for solving the intra-flow collisions in linear multi-hop wireless networks.



(a) (PER=0, $R_{\text{ir}} = 290$m)



(b) (PER=0.1, $R_{\text{ir}} = 290$m)

Figure 3.9. Throughput Comparison Given Different PER under Large Interference Range

Chapter 4

Synchronized Multi-Hop Protocol in Time-variable Multi-rate Networks

4.1 Bearable Rate Variance of E-SMHP

4.1.1 Theoretical Analysis of the Bearable Rate

In this section, the synchronization characteristics of E-SMHP are studied theoretically and it is shown that E-SMHP is robust in environments, where the transmission rates of the nodes change dynamically and are different from each other.

When the transmission rates are time-variable, the synchronized transmissions that E-SMHP tries to achieve may fail from time to time, and E-SMHP may retrograde back to RB-MAC in the worst case. However, E-SMHP is still robust against such rate variation for the following 2 features.

Firstly, E-SMHP regulates that, whenever Node 2 generates an RTS to its downstream node, the S_CTS mechanism notifies Node 0 of the completion time of the transmission from Node 2 to Node 3. That is to say, even if the synchronization is disrupted from time to time, S_CTS mechanism can recover the synchronization at the start of transmissions from Node 0 and Node 3 every time after Node 2 succeeds in a complete transmission of a data frame.

Secondly, E-SMHP can maintain synchronization of two nodes that are three-hop apart in a multi-hop network if the transmission rate of the downstream node is

conditionally lower than that of the upstream node. This synchronization maintenance is illustrated by an example in Fig.4.1. In the figure, if the transmission of DATA 1 by Node 3 is completed before the start of the RTS transmission by Node 1, then there will be collision at neither Node 2 nor Node 3 as far as DATA 1 and DATA 2 are concerned. This condition about the sequence of DATA 1 transmission by Node 3 and the start of RTS transmission by Node 1 is formulated as follows.
Whether the synchronized transmission will continue to succeed at Nodes 1 and 4 depends on the transmission timings at Nodes 0 and 3, and the condition is given by inequality (4.1).

$$T_{\text{DATA 2 at Node 0}} + \text{SIFS} + T_{\text{ACK}} + \text{DIFS} \geq T_{\text{DATA 1 at Node 3}} \tag{4.1}$$

in which $T_{\text{DATA 2 at Node 0}}$ and $T_{\text{DATA 1 at Node 3}}$ denote the time cost of transmitting a data packet at Nodes 0 and 3, respectively. It is assumed that, Nodes 0 and 3 generate RTSs simultaneously.
Given a transmission rate at Node 0, the minimum threshold of the transmission rate at Node 3 can be calculated by inequality (4.1). As long as the transmission rate at Node 3 is higher than the threshold, inequality (4.1) is satisfied, the data transmission at Node 3 can finish earlier, and thus there will be no collision when Node 0 finishes its transmission and Node 1 starts to relay.

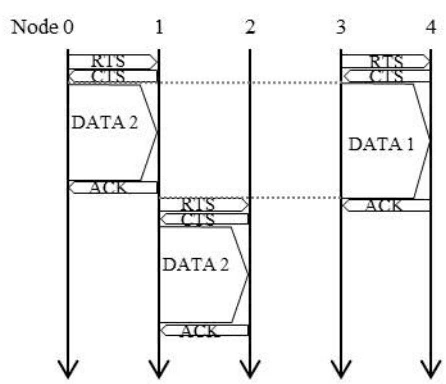


Figure 4.1. The Sequence Diagram of E-SMHP under Different Transmission Rates

According to IEEE 802.11g Standard, the transmission rate of data packets may be 6Mbps, 9Mbps, 12Mbps, 18Mbps, 24Mbps, 36Mbps, 48Mbps or 54Mbps [36-37]. For different transmission rates of Node 0, it is possible to derive different thresholds for the transmission rate of Node 3 in order to satisfy inequality (4.1). Table 4.1 shows the transmission rates (TR) of Node 0, the threshold rates at Node 3 for inequality (4.1) and the allowable choices of the rates at Node 3 to satisfy inequality (4.1), given that the data packet size is equal to 1,500byte. Table 4.1 tells us that, when the transmission rates of nodes vary between 36Mbps and 54Mbps, or between 24Mbps and 48 Mbps, the synchronized transmissions among nodes may not be disturbed in most cases. However, if the transmission rates of nodes vary between 18Mbps and 36Mbps, the throughput may deteriorate significantly since the probability for satisfying inequality (4.1) becomes small. Such phenomenon is demonstrated by simulations in Chapter 4.1.2.

It should be noted that there may be a collision between a downstream node and its three hop apart upstream node if the transmission rate of the downstream node is lower than that of the upstream node in two or more continuous synchronized transmissions.

On the other hand, Table 4.2 shows the same rates as those in Table I for the case where the data packet size is 1,000byte.

Tables 4.1 and 4.2 together show that, when the data packet size becomes smaller, the range of transmission rates for satisfying inequality (4.1) becomes wider for downstream nodes and the throughput is expected to remain more close to the theoretical upper limit. However, when the data packet size is smaller, the upper limit itself is smaller.

The data packet size is decided by various factors including the upper layer applications and the transmission quality, and it may not be determined by the MAC layer alone. However, if a smaller packet size is selected, the E-SMHP will provide a throughput that is very close to the theoretical upper limit, even if the transmission rates change significantly.

Table 4.1. Relationships of TRs at Synchronized Nodes(Packet Size=1500byte)

TR at N0	Threshold of TR at N3	Allowable TR at N3
54	25.463	36 and larger
48	24.046	36 and larger
36	20.606	24 and larger
24	16.021	18 and larger
18	13.105	18 and larger
12	9.607	12 and larger
9	7.584	9 and larger
6	5.336	6 and larger

Table 4.2. Relationships of TRs at Synchronized Nodes(Packet Size=1000byte)

TR at N0	Threshold of TR at N3	Allowable TR at N3
54	20.360	24 and larger
48	19.444	24 and larger
36	17.130	18 and larger
24	13.838	18 and larger
18	11.607	12 and larger
12	8.777	9 and larger
9	7.057	9 and larger
6	5.069	6 and larger

4.1.2 Experimental Results and Discussions

This subsection evaluates the throughput of E-SMHP under the environment with a packet size of 1,500byte. The transmission rate will change randomly at a period of 100 packets. Namely, every time after the destination node successfully receives 100 packets, all the nodes will randomly change their transmission rates independently from each other.

Figs. 4.2 and 4.3 show the throughputs of the theoretical upper limit, E-SMHP, RB-MAC and IEEE 802.11 DCF under IEEE 802.11g Standard given different ranges of transmission rates.

The throughput is the total received data packet bits at the destination node divided by the simulation duration, as rewritten by Eq (4.2), it is the same as Eq

(3.3).

$$\text{Throughput}_{\text{end-to-end}} = \frac{N_{\text{pkt}} \times S_{\text{pkt}}}{T_{\text{simulation}}} \tag{4.2}$$

where N_{pkt} denotes the total number of received data packets at the destination, S_{pkt} denotes the size of the data frame, $T_{\text{simulation}}$ denotes the simulation duration. The small dot line in Fig.4.2 denotes the theoretical upper limit a multi-hop wireless network based on IEEE 802.11 Standards can achieve with neither backoff nor collisions. A two-hop wireless network can achieve at most half of the throughput of a one hop network. A wireless network with three or more hops can achieve one third of the throughput in one hop network. The throughput of the conventional IEEE 802.11 DCF is always the lowest among the four and decreases if the number of hops increases.

In Fig 4.2, after receiving 100 packets successfully at the destination node, all nodes in the network randomly change their transmission rates among 36Mbps, 48Mbps and 54Mbps independently. In accordance with the theoretical analysis in Table 4.1, E-SMHP is capable of maintaining high throughput close to the upper limit, if the transmission rates vary from 25.463Mbps to 54Mbps. When the number of hops is 9, the throughput of E-SMHP outperforms conventional DCF by 259%, and RB-MAC by 18%, respectively.

On the other hand, Fig.4.3 shows the throughput of E-SMHP compared with other methods, when the transmission rates of all the nodes randomly change among 24Mbps, 36Mbps and 48Mbps, every time when 100 data packets are successfully received by the destination node.

According to Table 4.1, when the upstream transmission rate is 48Mbps, the minimum downstream transmission rate of E-SMHP is 24.046Mbps. Therefore, in Fig.4.3, the throughput can remain very close to the upper limit when the number of hops is 3 or 4. However, the larger the number of hops becomes, the smaller the throughput will be. This is because, when the number of hops increases, the possibility that the transmission rates of the downstream nodes are continuously smaller than upstream nodes also increases. According to Fig.4.1, E-SMHP may be able to avoid a collision when Node 0 transmits at the rate of 48Mbps and Node 3 transmits at the rate of 36Mbps. However, if Node 1 continues to relay at 48Mbps while Node 4 transmits at a slower rate again, collisions will happen.

Nevertheless, S_CTS mechanism will recover the synchronized transmission when Nodes 3 and 0 start generating RTS again. In the worst case, there is a collision immediately after the synchronization is recovered. Then the throughput of E-SMHP will degrade considerably, however, to no less than that of RB-MAC because RB-MAC is incorporated in Principle 2 of E-SMHP. Besides, in most cases, S_CTS can work efficiently. Therefore, in Fig.4.3, although the throughput of E-SMHP degrades, it still outperforms RB-MAC by 11% when the number of hops is as large as 9.

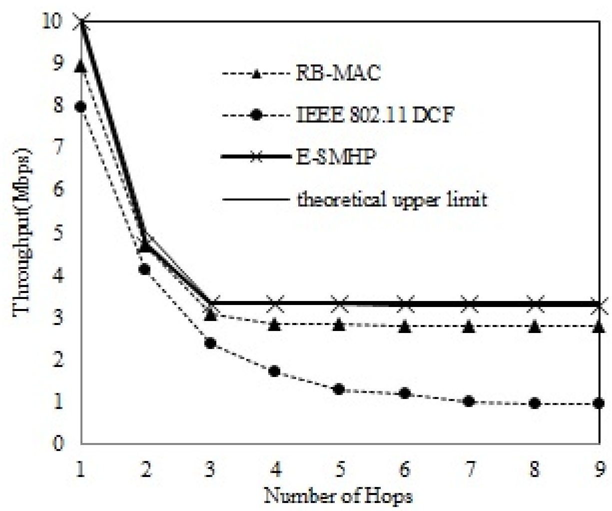


Figure 4.2. Throughput Comparison (Transmission Rate = 36Mbps, 48Mbps, or 54Mbps; Data Packet Size =1,500byte)

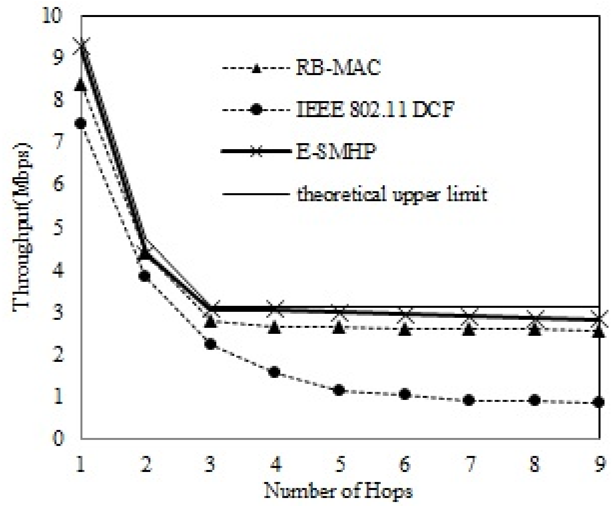
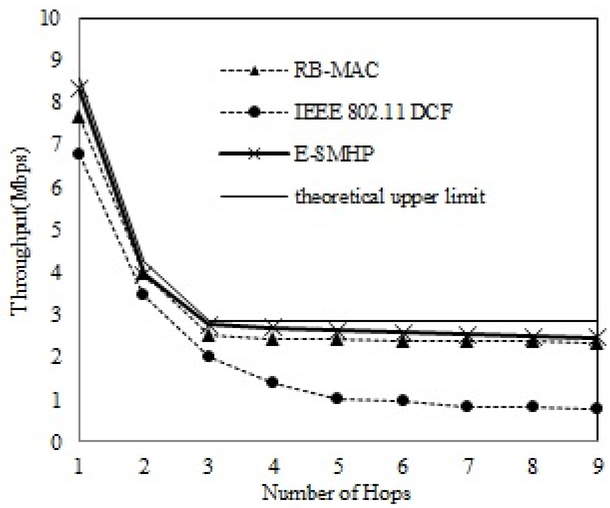


Figure 4.3. Throughput Comparison (Transmission Rate = 24Mbps, 36Mbps or 48Mbps; Data Packet Size =1,500byte)

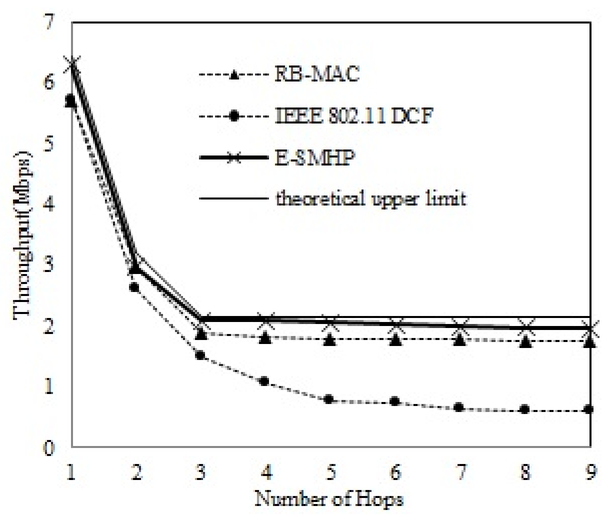
Fig.4.4(a) shows the throughputs when the data packet size is 1,500byte, and the possible transmission rates are 18Mbps, 24Mbps or 36Mbps. On the other hand, Fig.4.4(b) shows the throughputs with the same conditions as those in Fig.4.4(a), except for the data packet size of 1,000byte.

When the number of hops is 9, the throughput of E-SMHP is around 87% of the upper limit in Fig.4.4(a), while in Fig.4.4(b), E-SMHP can achieve around 92% of the upper limit. This result is in accordance with the analysis in Chapter 4.1.1. As observed from Tables 4.1 and 4.2, the smaller the data packet size is, the wider the allowable fluctuation range of the random transmission rate is for E-SMHP to maintain high throughput.

Therefore, it is recommended that the network should be designed so that the transmission rates are always within the range that can be derived by inequality (4.1).



(a) Data Packet Size =1500byte



(b) Data Packet Size =1000byte

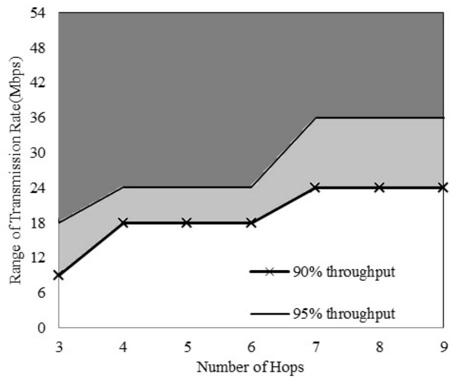
Figure 4.4. Throughput Comparison with Multiple Data Packet Sizes when TR=18, 24 or 36Mbps

Fig. 4.5(a) shows the allowable range of transmission rates when the packet size=1,00byte, Fig. 4.5(b) shows the allowable range of transmission rates when the packet size=1,500byte, while Fig. 4.5(c) shows the allowable range of transmission rates when the packet size=2,346byte, which is the fragmentation threshold for IEEE 802.11 Standards, i.e. the maximum packet size.

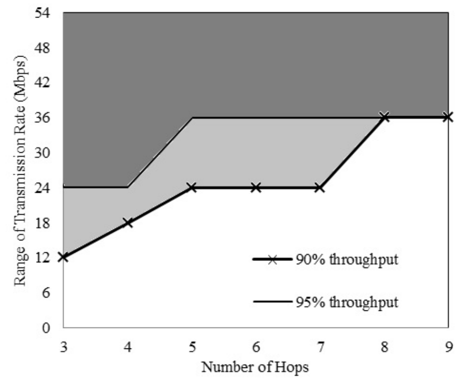
Fig. 4.5(b) means that, when the number of hops is 3, to achieve 90% of the upper limit of throughput, transmission rates are allowed to vary from 12, 18, 24, 36, 48, to 54Mbps, while to achieve 95% of the upper limit of throughput, transmission rates are allowed to vary from 24, 36, 48 to 54Mbps. Such variation range will shrink to only 36∼54Mbps if the number of hops becomes 9.

Also, the comparison of Fig. 4.5(a)∼(c) show that the larger the data packet size is, the smaller the allowable range is. When the packet size is 2,346byte, the number of hops is 3, transmission rates must be between 18 and 54Mbps to maintain 90% upper limit, and between 24 and 54Mbps to maintain 95% upper limit. The allowable range is also 36∼54Mbps if the number of hops is 9.

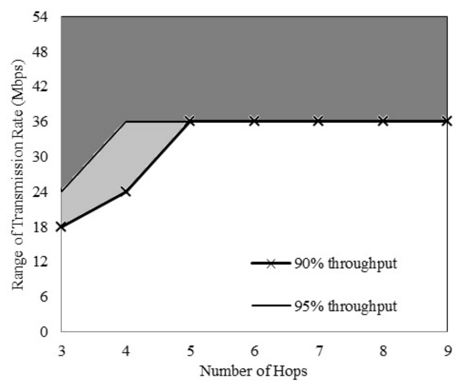
However, it does not mean that because the allowable range for smaller packet size is larger, it is always preferable to choose smaller packet size. Since larger packet size offers larger throughput under the same transmission rate, the packet size should be chosen according to the actual demands of the environment.



(a) Data Packet Size =1000byte



(b) Data Packet Size =1500byte



(c) Data Packet Size =2346byte

Figure 4.5. Allowable Transmission Range Given Different Data Packet Sizes

On the other hand, it is also useful if the allowable data packet size is known, when the transmission rates are restricted by the actual communication environment. Therefore, the allowable data packet size for satisfying 90% and 95% of the upper limit of throughput is shown in Fig.4.6 .

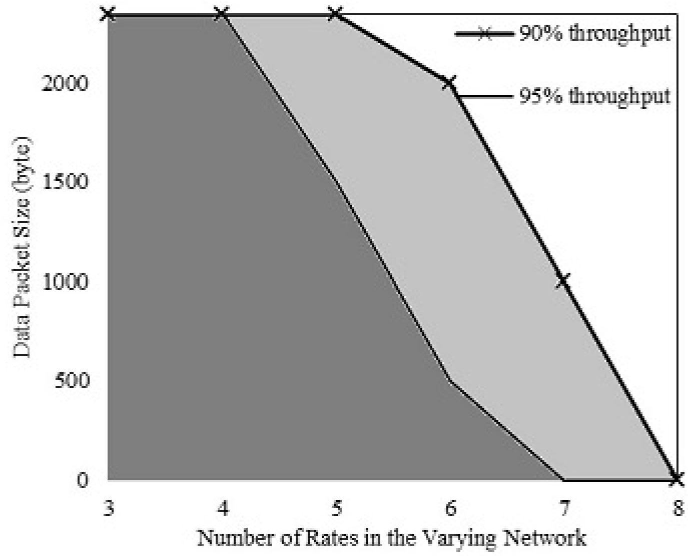


Figure 4.6. Allowable Data Packet Size

The x-axis of Fig.4.6 means the number of rate variation patterns, when the number=3, rates only vary among 54, 48, 36Mbps. On the other hand, if the number=8, the rates vary from 6,9,12,18,24,36,48 to 54Mbps randomly.

The dark block in the figure shows the allowable range of data packet size under different rates variation patterns, in order to achieve 95% of the upper limit of the throughput. The dark+light blocks in Fig.4.6 show the range of data packet size under similar situations to achieve 90% of the upper limit.

Given a certain rate variation patterns in an actual network, if higher accuracy of data transmission is required, then we can set the data packet size according to the dark grey block. However, if the networks requires higher throughput than accuracy, then the options in the light grey block can also be taken into consideration, because with larger packet size in the light grey block, higher throughput can be achieved with limited sacrifice of accuracy.

4.2 Extension of E-SMHP with S_ACK Control Frame

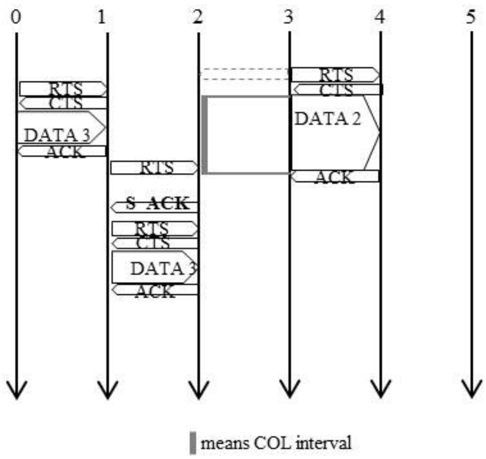
4.2.1 S_ACK Extension for Improving the Throughput of E-SMHP

In order to further improve the throughput in conditions beyond Table 4.1, i.e. in which the transmission rates vary in a larger scale so that there may be frequent transmission failures due to the low rate of downstream nodes, a new control packet named S_ACK is introduced when the number of hops is larger than 3.

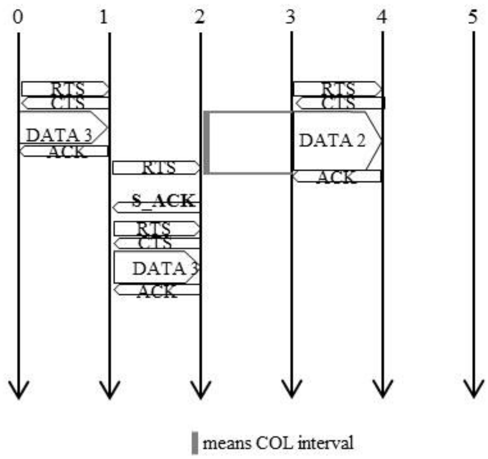
When the downstream data transmission is slow, so that the upstream RTS generation collides with the downstream data transmission and fails, S_ACK packet is introduced as a new control message, which will inform the upstream node of an earlier timing of RTS retransmission so that the useless waiting time after RTS failure can be avoided.

The conditions where S_ACK is necessary are analyzed in the rest of this section. In Fig. 4.7, Node 3's transmission rate is lower than Node 0's, therefore after the completion of Node 0's transmission, Node 1's RTS will always collide with Node 3's data at Node 2. The collision can be divided into 3 cases.

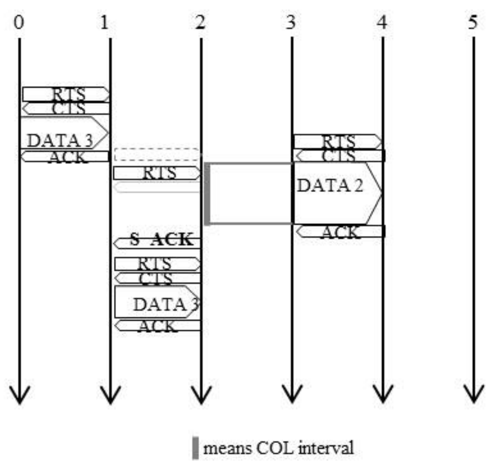
Because when a node is under a collided carrier sensing, like Node 2 in Fig. 4.7, it cannot tell what packets are colliding. The only information that is useful is the duration length of the collided carrier sensing. Therefore, S_ACK discriminant will be triggered if no packets are received/overheard when the carrier sensing ends. After discrimination, if the collision fits into one of the 3 cases shown in Fig. 4.7, S_ACK will be triggered to its upstream node by the collision node. If S_ACK is successfully received by the upstream node (Node 1 in Fig. 4.7), the node (Node 1) will immediately retransmit RTS after DIFS.



(a) Node 1's CTS, ACK and RTS collide with Node 3's DATA2 at Node 2



(b) Node 1's ACK and RTS collide with Node 3's DATA2 at Node 2



(c) Node 1's RTS collides with Node 3's DATA2 at Node 2

Figure 4.7. Three Cases Where S_ACK is Necessary

The critical conditions for cases (a) to (c) are shown as follows. N1_CTS=1 or 0 means CTS, which has been generated by Node 1, is overheard successfully or not at Node 2 from the ending time of its own transmission to the ending time of the current collision, N1_ACK=1 or 0 means ACK generated by Node 1 is overheard or not at Node 2 during the same period, N3_RTS=1 or 0 means RTS generated by Node 1 is overheard or not at Node 2 during the same period, col_time denotes the duration of the collided time, data_time means the array containing the duration for transmitting data at 8 different transmission rates, assuming packet size=1500byte.

Case (a):
N1_CTS=0, N1_ACK=0, N3_RTS=1,
col_time> *time*(CTS+SIFS+DATA
at 54Mbps+SIFS+ACK+DIFS+RTS), i.e. col_time>1.142ms,
col_time!= element of data_time
Case (b):
(N1_CTS=1,N3_RTS=1)or(N1_CTS=0,N3_RTS=0,col_time!=element of data_time)
col_time> *time*(ACK+DIFS+RTS), i.e. col_time>0.48ms,
Case (c):
N1_ACK=1,
col_time> *time*(DATA at 54Mbps), i.e. col_time>0.422ms

However, in terms of case(b), sometimes even if the col_time is equal to the data transmission time, S_ACK is still necessary because the RTS from Node 1 to Node 2 may collide before the ending time of the data transmission from Node 3 to Node 4. However, if the command "col_time!= element of data_time" is not applied in the critical conditions of case (b), the situation where N1_CTS=0, N3_RTS=0, and col_time>0.48ms but S_ACK is actually not necessary will frequently occur. What's worse, if the S_ACK is unnecessarily sent in this situation, it will not only disturb the current transmission between Node 0 and Node 1 in Fig.4.8, but also intervene the potential transmissions which are meant to be successful after the current time slot. Therefore, by adding "col_time!= element of data_time" in case (b), the S_ACK can be generated more accurately and the throughput can be further improved.

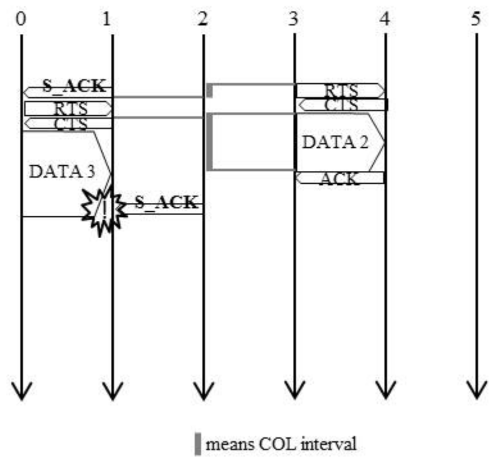


Figure 4.8. S_ACK Is Unnecessarily Sent If "col_time!= element of data_time" Is Not Applied in the Critical Conditions of Case(b)

After the ending time of a collided carrier sensing, if Node 2 discovers that the col_time and the overheard packets satisfy the critical conditions of cases (a) or (b), Node 2 will run into a special IFS=*time*(RTS+DIFS), and if during the IFS, no RTS from Node 1 is received by Node 2, then S_ACK will be generated from Node 2 to Node 1.

Such long IFS is important for S_ACK because, in Fig. 4.7 (a) and (b), if DATA2 from Node 3 only collides with CTS or ACK from Node 1, it is still possible that the critical conditions shown in case(a) and (b) are satisfied. If it is the case that only CTS or ACK from Node 1 collides, then during *time*(RTS+DIFS), Node 2 should be able to receive an RTS from Node 1. Therefore, a waiting of *time*(RTS+DIFS) is important to avoid such mis-discrimination.

If after the ending time of a collided carrier sensing, Node 2 discovers that the col_time and the overheard packets satisfy the critical condition of case (c), it will generate S_ACK after an IFS=*time*(SIFS+ACK), in order to avoid collision with the ACK from Node 4 to Node 3.

4.2.2 Experimental Results and Discussions

Given the same simulation environments as shown in Table 2.3, throughputs of E-SMHP with S_ACK, E-SMHP, RB-MAC and DCF are shown in Fig. 4.9. The data packet size is 1500byte, transmission rates vary from 18Mbps to 54Mbps.

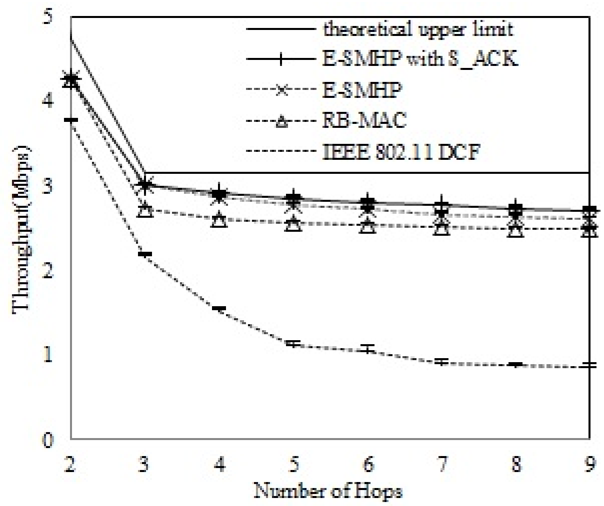


Figure 4.9. Throughputs of E-SMHP with S_ACK and Previous Methods

The 95% confidence intervals are also drawn in Fig. 4.9, since 1000-second simulation gives stable simulation results, the confidence intervals are very narrow. The confidence interval are calculated by repeating the 10-second simulation for 100times, so that the average throughput of the 100-time simulations $\bar{H}$ and the standard deviation σ are calculated, then the 95% confidence interval is equal to $H \pm 2(\sigma/\sqrt{n})$.

One important detail is that, the standard deviation σ is calculated by the following formula,

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{4.3}$$

in which the denominator is "$N-1$" instead of N, because if it's divided by N, it only means the average of sampled data, in other words, it is a biased estimator. Bessel[38] has shown that, if we multiply the variance by $\frac{N}{N-1}$, equivalently, using $\frac{1}{N-1}$ instead of $\frac{1}{N}$, it gives an unbiased estimator.

From Fig. 4.9, when the number of hops is 9, E-SMHP with S_ACK outperforms E-SMHP by 4%, outperforms RB-MAC by 9%, outperforms DCF by 214%, respectively. Even if E-SMHP with S_ACK generates S_ACK control packets only when necessary, the retransmission of some frames by nodes which receive S_ACK may lead to collision with its upstream nodes again. In fact, such collisions happen frequently when S_ACK are sent, because any nodes within 2 hops may intervene, and the possibility that the backoff timers of the neighboring nodes within 2 hops do not expire during the retransmission is very low. Besides, the transmission of S_ACK control packet itself also consumes some time.

Nevertheless, the overall throughput of E-SMHP is improved by S_ACK extension, and E-SMHP with S_ACK outperforms any of the existent methods.

Chapter 5

Conclusions

In this thesis, we have firstly introduced the throughput deterioration problem caused by intra-flow collisions in multi-hop wireless networks. A MAC layer protocol called SMHP is proposed to solve the problem. The results and analysis in Chapter 3.1 show that, SMHP is capable of completely solving the problem under ideal environment. The throughput is improved to be very close to the upper limit, when the number of hops is equal to 5 under IEEE 802.11g environment, SMHP outperforms the conventional DCF by 84%.

Later, in order to improve the application of SMHP in environments with transmission failures caused by noise or interference from the actual communication environment, or large interference range, the SMHP method is extended to E-SMHP, which is capable of providing stable throughputs which are all very close to the upper limit. Even in the worst case, when PER is equal to 0.1, the interference range is about 2 times of the transmission range, the throughput is still stable and E-SMHP outperforms the conventional DCF by 96.3% when the number of hops is equal to 9.

Finally, the application of E-SMHP under environments where the transmission rates are time-variable and may vary from node to node is estimated. It is discovered that, the conventional E-SMHP is capable of providing stable throughputs as long as the transmission rates vary in a certain range. For example, when the data packet size is 1,500byte, transmission rates may randomly vary from 36, 48 to 54Mbps, E-SMHP can perform stably, provides throughputs not only very close to the upper limit, but outperforms DCF by 259% when the number of hops is equal to 9.

In order to strengthen E-SMHP's advantages over the previous methods even if the transmission rates vary more arbitrarily. A control frame called S_ACK is proposed to further improve the throughput of E-SMHP. The critical conditions for generating S_ACK control frame is carefully studied, so it may be and may only be triggered to notify the upstream node when the downstream node transmits at a slower rate, in this way the upstream node may be able to retransmit more efficiently. An example in Chapter 4.2.2 shows that E-SMHP with S_ACK is capable of providing a throughput which outperforms DCF by 214% when the transmission rates randomly vary from 18, 24, 36, 48 to 54Mbps, and the number of hops is equal to 9.

These high throughputs in environments with high PER, large interference range or random transmission rates achieved by SMHP, E-SMHP, and E-SMHP with S_ACK are considered of high originality, since there have been no research papers to cover the study on the throughputs of such a network.

In conclusion, E-SMHP with S_ACK is considered a mature enough solution for solving the intra-flow collisions in linear multi-hop wireless networks, even if the packet error rate is high, the interference range is large, or the transmission rate is time-variable and may vary from node to node.

The throughput of a lot of linear multi-hop wireless network applications can be improved accordingly, e.g. the long hop mesh networks or the environment/earth monitoring of wireless sensor networks [39].

Chapter 6

Future Work

E-SMHP with S_ACK is designed for a linear network with single flow of data transmission. It is thus expected to be further extended to cover multi-flow dimensions of non-linear networks, and such a proposal with further extensions should be applicable to more areas.

The radio propagation in current experiments is based on the Two-Ray Ground reflection model, more complicatied radio propagation model may be expected. Also, the nodes in current experiments are not movable, if it is possible to extend current method to the environemnts with mobility model, the application of current method will be dramastically improved.

Another possible future work of this research is to find out the most appropriate way of network configuration including the topology, QoS and every possible condition in order to achieve the best performance of the E-SMHP with S_ACK method.

Appendix A

Publications

International Conferences

[1] X.Yao, Y. Wakahara, "Application of Synchronized Multi-Hop Protocol to Time-Variable Multi-Rate and Multi-Hop Wireless Network", in Proc. of IEICE APNOMS Conference, Hiroshima, Japan, Sep. 2013.

[2] X.Yao, Y. Wakahara, "Synchronized Multi-Hop Protocol with High Throughput for an IEEE 802.11 Multi-Hop Wireless Network", in Proc. of IEEE Smart Communications in Network Technologies, Paris, France, Jun. 2013.

Domestic Conferences

[3] X.Yao, Y. Wakahara, "Application of Synchronized Multi-Hop Protocol to Multi-Hop Wireless Network with Variable Transmission Rates", in Proc. of IEICE Society Conference, Fukuoka, Japan, Sep. 2013.

[4] X.Yao, Y. Wakahara, "Analysis of Synchronized Multi-Hop Protocol and Proposal of Its S_ACK Extension under Time-Variable Multi-Rate and Multi-Hop Wireless Network", in Proc. of IEICE RCS Conference, Nagano, Japan, Aug. 2013.

[5] X. Yao, Y. Wakahara, "Modified Synchronized Multi-Hop Protocol for IEEE 802.11 based Multi-Hop Wireless Network", in Proceedings of IEICE General Conference, Gifu, Japan, March 2013.

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[10] X.Yao, Z. Liang, and Y. Wakahara, "Proposal for Improving Throughput of Multi-Hop Wireless Network," IEICE Technique Report(IN), Tokyo, Japan, May 2012, IN2012-20, pp.49-54.

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