

# Application of Synchronized Multi-Hop Protocol to Time-Variable Multi-Rate and Multi-Hop Wireless Network

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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 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 where 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. In this paper, the protocol is applied to the environment where the transmission rate of data packets is time-variable and may be different from node to node. By theoretical analysis and simulation experiments, the throughput of the protocol is confirmed high and it is very close to its theoretical upper limit if the variation of the transmission rate is restricted within a certain range.

**Keywords**— multi-hop wireless network; IEEE 802.11 DCF; synchronized multi-hop protocol, variable rate, multi-rate

## I. INTRODUCTION

Multi-hop wireless networks are promising for the next generation communication because of its self-organized characteristics, which enable the network to be applicable to especially hard-to-wire situations. There are strong demands for the network from commercial applications such as community wireless networks [1], sensor networks [2], and military applications such as battle field communications. Despite the promising application prospects, an actual multi-hop wireless network built under the present IEEE 802.11 framework is faced with a severe throughput deterioration problem. Previous related researches have discovered that the deterioration is caused by inter- and intra-flow collisions [3-4].

Media Access Control (MAC) provides a channel access control mechanism, which has a dominant effect on the throughput of the network. IEEE 802.11 Request-To-Send (RTS)/Clear-To-Send(CTS)/Data/Acknowledgement(ACK) 4-way handshake was designed to alleviate the hidden terminal problem [5]. In practice, the conventional IEEE 802.11 Standards are not sufficient for solving the throughput deterioration problem, and a lot of improved MAC protocols have been proposed [6-11]. However, most of these so far proposed methods cannot solve the intra-flow collisions to a satisfying extent as analyzed in Section II [12-14].

In [15-17], a new MAC layer protocol E-SMHP (Extended Synchronous Multi-Hop Protocol) is proposed to provide high throughput with a slight modification on the conventional IEEE 802.11 DCF. It has been shown that E-SMHP achieves high throughput, which is close to its theoretical upper limit, even in the cases with transmission errors and large interference range, assuming that the transmission rates are the same for all the nodes. In practice, however, the transmission rates usually change dynamically depending on the transmission quality, the receiving signal levels etc. As far as the authors know, there is no paper discussing the technology to achieve high throughput in the case where the transmission rates of the multi-hop wireless networks dynamically change. Thus, the purpose of this paper is set to study and prove the conditions of the high throughput of E-SMHP even if the transmission rates of the network change randomly.

The rest of this paper is organized as follows. The throughput deterioration problem of the current networks is described and the existing methods are discussed in Section II. Section III briefly reviews the E-SMHP method. Section IV gives the theoretical analysis of the performance of E-SMHP in environments where the transmission rates may vary randomly. Then, Section V introduces the evaluations comparing E-SMHP with the existing methods. Finally, the conclusion is drawn in Section VI.

## II. PROBLEM OF THE LINEAR MULTI-HOP WIRELESS NETWORK AND ITS EXISTING SOLUTIONS

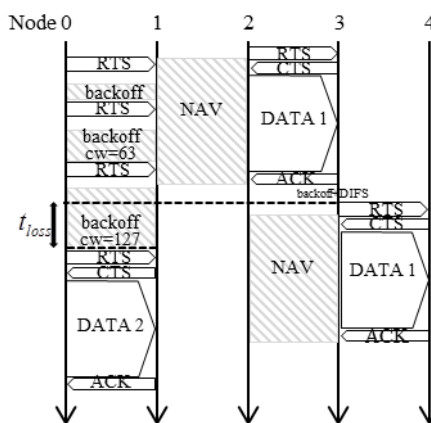


Fig. 1. A sequence diagram example of a linear IEEE 802.11 multi-hop wireless network.

It is well-known that the dominant reason for the throughput deterioration in a linear IEEE 802.11 multi-hop wireless network is intra-flow collisions, where the linear network consists of some nodes in a line segment and data are forwarded from one end node to the other end node by the relay of all the other nodes along the line.

An example of the network is elaborated in Fig.1, where Nodes 0 and 4 are the source and the destination for data transmission, respectively. Node 2 starts to transmit DATA1 to Node 3. Then Node 0 attempts to transmit DATA 2 to Node 1 almost at the same time.

In IEEE 802.11 DCF, Network Allocation Vector (NAV) is used to avoid collisions. Therefore Node 1 is blocked because of the NAV embedded in the overheard RTS from Node 2. Thus, the first attempt of RTS by Node 0 fails, followed by the backoff timer based on a contention window (CW).

Furthermore, the CW will increase exponentially every time the transmission fails. Namely, collision between RTS of Node 0 and RTS/DATA of Node 2 leads to the increase in backoff timer and eventually to a period of time loss shown as  $t_{loss}$  in Fig.1. In addition, if the number of failures reaches Station Short Retry Count (SSRC), which is usually 7, the wireless link is considered broken and routing protocols such as AODV will reestablish the path [18]. Such extended backoff timer and routing protocol overhead are the largest causes for the throughput deterioration of a linear IEEE 802.11 multi-hop wireless network.

There are various methods proposed to solve the above throughput deterioration problem [6-14]. However, most of them still cannot provide satisfying throughput because they cannot solve the intra-flow collisions in Fig.1 thoroughly.

Recently, [14] proposed a protocol called RB-MAC, which is designed for eliminating the intra-flow collisions by forwarding the data packets immediately after receiving them. This protocol seems effective and its throughput is actually higher than that of other existing protocols. However, there can still be some transmission collisions among nodes by RB-MAC, an example is shown in Fig.1 and this makes the throughput not high enough.

The transmission rate has always been made fixed in previous researches. However, in practice, the transmission rate is usually variable in accordance with e.g. the real-time transmission and reception quality. Therefore, the throughput of the existing protocols designed for improving the throughput is not always optimal in such practical cases.

### III. SYNCHRONIZED MULTI-HOP PROTOCOL (SMHP)

#### A. Synchronized Multi-Hop Protocol (SMHP)

Synchronized Multi-Hop Protocol (SMHP) has the following two main principles. Except for the modifications based on these principles, the SMHP is in complete accordance with the conventional IEEE 802.11 Standards.

- Principle 1: If the second node (Node 1 in Fig.2) from the source overhears an RTS message generated by its

downstream node (Node 2), this overhearing node sends a newly defined control frame named S\_CTS back to the source node (Node 0) in order to inform the source node of the ongoing two-hop away transmission (from Node 2 to Node 3). S\_CTS has a NAV whose expiring time is the same as that of the NAV in the RTS overheard by the second node (Node 1). Then the source node (Node 0) becomes able to access the channel again after the NAV in S\_CTS expires.

- 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 a node has just recovered from the NAV of S\_CTS.

Principle 1 is designed to notify Node 0 in Fig.1 of the ongoing transmission at Node 2, so that neither useless RTS attempt nor extended backoff will be generated. The duration information of data transmission by Node 2 is stored in its RTS frame as NAV. This RTS frame is overheard by Node 1, and the NAV information is forwarded to Node 0 through S\_CTS.

S\_CTS requires a longer inter-frame space (IFS) than SIFS at the second node (Node 1) from the source (Node 0) in order to avoid collision with the ongoing reception of a message (e.g. CTS reception) at Node 2. The inter-frame space of S\_CTS  $S_{SIFS}$  is defined by equations (1) and (2).

$$S_{SIFS} = SIFS + T_{CTS} + SIFS \quad (1)$$

$$NAV_{S\_CTS} = NAV_{RTS} - S_{SIFS} - T_{S\_CTS} \quad (2)$$

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

Principle 2 is designed for eliminating unnecessary waiting. 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 causing any channel conflict. Thus, the extension of backoff timer is avoided, and such saved time further contributes to the throughput improvement.

Principles 1 and 2 are called S\_CTS mechanism and Prioritized Backoff, respectively. The synchronization among nodes with the distance of three hops realized by Principle 1, and the elimination of unnecessary backoff of Principle 2 are the most crucial reasons for the effectiveness of SMHP.

#### B. Extension of SMHP against Transmission Failures

Transmission of a message may fail when there exist inter-flow and intra-flow collisions or noise in the channel. Therefore, the extension of SMHP is proposed to react against the transmission failures and to achieve their fast recovery [16].

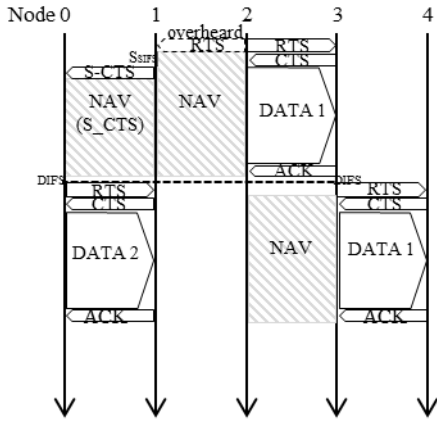


Fig. 2. The sequence diagram of S\_CTS mechanism

As shown in Fig.3, the principle of the proposed fast recovery is to force a node (e.g. Node 3), which has detected a data transmission failure, to retransmit the failed frame immediately after the detection. On the other hand, a node with an RTS transmission failure (e.g. Node 1) retransmits the RTS after a pre-determined period  $T_e$ .

$$T_e = SIFS + T_{DATA} + SIFS + T_{ACK} \quad (3)$$

where  $T_{DATA}$  denotes the time for transmitting one data frame using the maximum data transmission rate, i.e. 54Mbps in IEEE 802.11g Standard, and  $T_{ACK}$  denotes the time for one ACK frame transmission.

This protocol is named E-SMHP and E-SMHP has been shown robust in the environment where there is high Packet Error Rate as well as large interference range.

#### IV. APPLICATION OF E-SMHP TO TIME-VARIABLE MULTI-RATE AND MULTI-HOP WIRELESS NETWORK

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

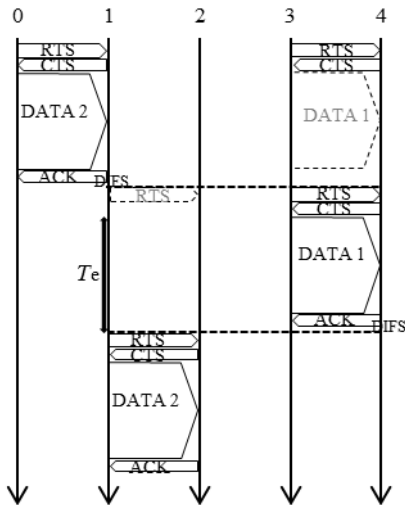


Fig. 3. The sequence diagram of the fast recovery mechanism of Extended SMHP.

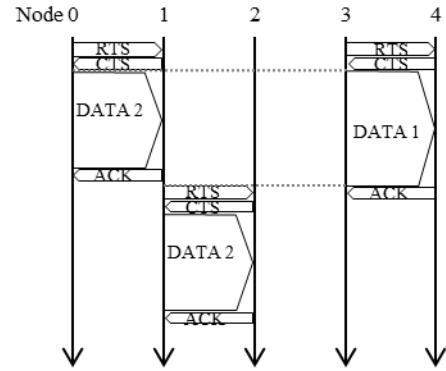


Fig. 4. The sequence diagram of E-SMHP under Different Transmission Rates.

When the transmission rates are time-variable, the synchronized transmissions that E-SMHP tries to achieve may fail from time to time. 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. 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 no collision at either Node 2 or Node 3 as far as DATA 1 and DATA 2 are concerned. This condition about the sequence of DATA 1 by Node 3 and the 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).

$$T_{DATA2 \text{ at Node } 0} + SIFS + T_{ACK} + DIFS \geq T_{DATA1 \text{ at Node } 3} \quad (4)$$

in which  $T_{DATA2 \text{ at Node } 0}$  and  $T_{DATA1 \text{ at Node } 3}$  denote the time cost of transmitting a data packet at Nodes 0 and 3, respectively. Nodes 0 and 3 generate RTSs simultaneously because of S\_CTS mechanism.

Given a transmission rate at Node 0, the minimum threshold of the transmission rate at Node 3 can be calculated by inequality (4). As long as the transmission rate at Node 3 is higher than the threshold, inequality (4) is satisfied, the data transmission at Node 3 can finish earlier, thus there will be no collision when Node 0 finishes its transmission and Node 1 starts to relay.

According to IEEE 802.11g Standard, the transmission rate of data packets may be 6, 9, 12, 18, 24, 36, 48 or 54Mbps [19-

20]. For different transmission rates of Node 0, it is possible to derive different thresholds of the transmission rate of Node 3.

Table I shows the TRs (transmission rates) of Node 0, the threshold rates at Node 3 for inequality (4) and the allowable choices of the rates at Node 3 to satisfy inequality (4), given that the data packet size is equal to 1,500byte. Table I 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) becomes small. Such phenomenon is demonstrated by simulations in Section V.

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 II shows the same rates as those in Table I for the case where the data packet size is 1,000Byte.

As shown in Tables I and II, when the data packet size becomes smaller, the range of transmission rates for satisfying inequality (4) 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 affected 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.

## V. THROUGHPUT EVALUATION OF THE PROPOSALS

For the purpose of demonstrating the efficiency of E-SMHP in comparison with some existing methods, simulations have been conducted for IEEE 802.11g based networks with time-variable transmission rates of the individual nodes. Parameters of the simulation scenario are given in Table III. The network topology is linear, and all the 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. It is assumed that only one channel is available for this network and all the nodes have non-directional antennas. NS 2.34 is used in the simulations [21].

### A. Performance under Different Data Rates

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.

TABLE I. RELATIONSHIPS OF TRANSMISSION RATES (TRs) AT SYNCHRONIZED NODES (PACKET SIZE = 1,500BYTE)

TR at Node 0 (Mbps)	Threshold of TR for Node 3 (Mbps)	Allowable TR at Node 3 (Mbps)
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 II. RELATIONSHIPS OF TRANSMISSION RATES (TRs) AT SYNCHRONIZED NODES (PACKET SIZE = 1,000BYTE)

TR at Node 0 (Mbps)	Threshold of TR for Node 3 (Mbps)	Allowable TR at Node 3 (Mbps)
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

TABLE III. SIMULATION SCENARIO BASED ON IEEE 802.11G

Parameter	Value
Topology	Linear
Radio Propagation Model	Two-Ray Ground Reflection
No. of Channel	1
Transport Protocol	UDP
Data Generation Rate	12Mbps (CBR)
Routing Protocol	AODV
Distance between Neighbouring Nodes	100m
Transmission Range	150m
SIFS	0.01ms
DIFS	0.028ms
Slot Time	0.009ms
PLCP Rate	1Mbps
Basic Rate	4Mbps
Simulation Duration	1000s

Figs. 5 and 6 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 shown by equation (5).

$$\text{Throughput}_{\text{end-to-end}} = \frac{N_{\text{pkt}} \times S_{\text{pkt}}}{T_{\text{simulation}}} \quad (5)$$

where  $N_{\text{pkt}}$  denotes the total number of received data packets at the destination,  $S_{\text{pkt}}$  denotes the size of the data frame, and  $T_{\text{simulation}}$  denotes the simulation duration.

The small dot line in Fig.5 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 5, after receiving 100 packets successfully at the destination node, all nodes in the network randomly change their transmission rates among 36, 48 and 54Mbps independently. In accordance with the theoretical analysis in Table I, 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.6 shows the throughput of E-SMHP compared with other methods, when the transmission rates of all the nodes randomly change among 24, 36 and 48Mbps, every time when 100 data packets are successfully received by the destination node. According to Table I, when the upstream transmission rate is 48Mbps, the minimum downstream transmission rate of E-SMHP is 24.046Mbps. Therefore, in Fig.6, 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, 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.6, although the throughput of E-SMHP degrades, it still outperforms RB-MAC by 11% when the number of hops is as large as 9.

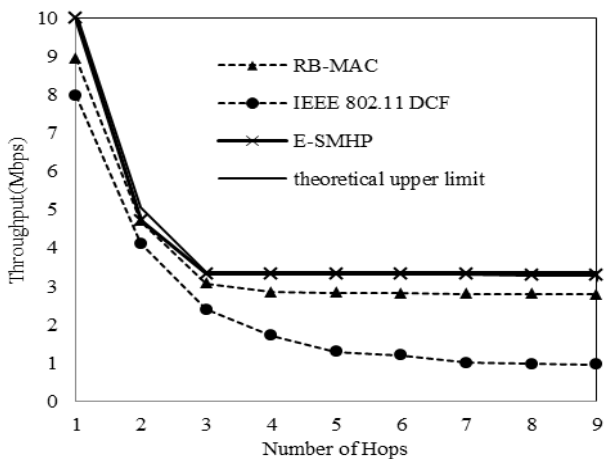


Fig. 5. Throughput comparison (transmission rate = 36, 48, or 54Mbps; data packet size = 1,500byte)

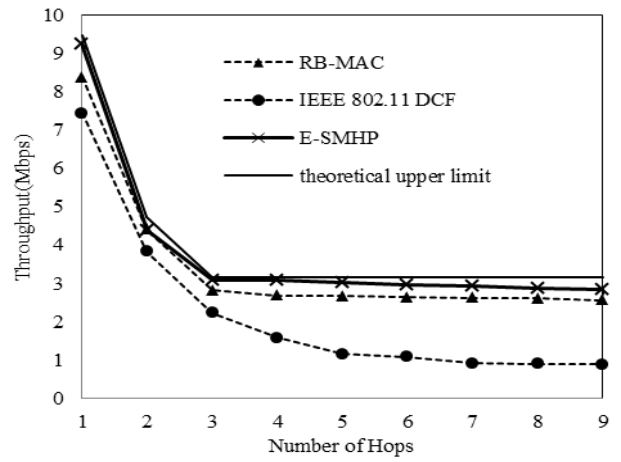


Fig. 6. Throughput comparison (transmission rate = 24, 36 or 48Mbps; data packet size = 1,500byte)

### B. Performance under Different Packet Sizes

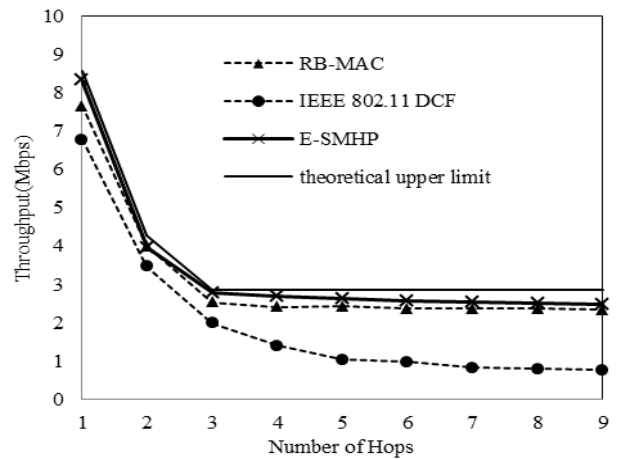


Fig. 7. Throughput comparison (transmission rate = 18, 24 or 36Mbps; data packet size = 1,500byte)

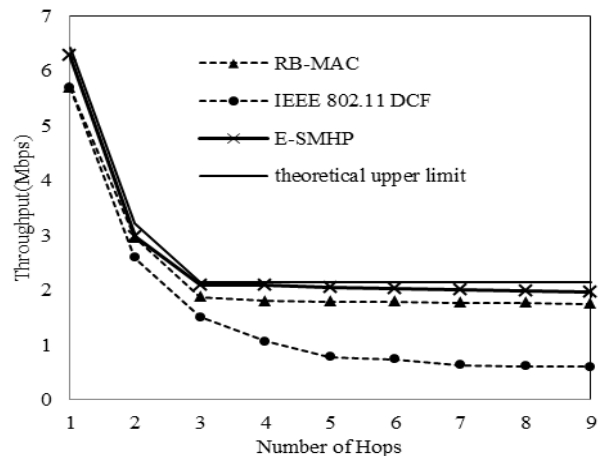


Fig. 8. Throughput comparison (transmission rate = 18, 24 or 36Mbps; data packet size = 1,000byte)

Fig.7 shows the throughputs when the data packet size is 1,500byte, and the possible transmission rates are 18, 24 or 36Mbps. On the other hand, Fig.8 shows the throughputs with the same conditions as those in Fig.7, 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.7, while in Fig.8, E-SMHP can achieve around 92% of the upper limit. This result is in accordance with the analysis in Section IV. As observed from Tables I and II, 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).

## VI. CONCLUSION AND FUTURE WORK

In this paper, E-SMHP is applied to a time-variable multi-rate and multi-hop wireless network. The transmission rates of the nodes are not necessarily same, and are time-variant from node to node in such network. It has been shown that, as long as the transmission rates are designed within the range in accordance with inequality (4), E-SMHP is capable of providing high throughput and that the throughput of E-SMHP is optimal among all the compared methods in every case. These results including inequality (4) are considered of high originality, since there have been no research papers to cover the study on the throughputs of such a network.

Thus E-SMHP 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[16], the interference range is large[17], or the transmission rate is changeable. 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 pipeline monitoring of wireless sensor networks [22].

E-SMHP is designed for a linear network with single flow of data transmission. E-SMHP 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. Therefore, future work on this research includes finding out the counteractions when multi-flow topologies are taken into consideration, and studying for improving higher layer throughput such as the TCP throughput for multi-hop networks.

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