Throughput Analysis of Dynamic Multi-Hop Network Under High Traffic Load

Yusuke Sunada, Koichi Adachi, and Yasushi Yamao
Advanced Wireless & Communication Research Center (AWCC)
The University of Electro-Communications
Chofu, Japan
y.sunada@uec.ac.jp, {adachi, yamao}@awcc.uec.ac.jp

***Abstract*—This paper theoretically analyzes the throughput of the dynamic multi-hop networks under high traffic load condition. In order to reduce the number of hops and improve the throughput performance, the shortcut path between the non-neighboring nodes is established. However, the preceding packet hinders the establishment of the shortcut path when the traffic load is high. To eliminate the interference from the preceding packet, we introduce intra-flow interference canceller (IFIC). We derive the theoretical packet delivery rate (PDR) expression by taking into account the existence of preceding packets. Theoretical analysis and numerical evaluation elucidate the effectiveness of IFIC to improve the throughput performance in dynamic multi-hop networks even under high traffic load condition.**

***Index Terms*—Dynamic multi-hop network, intra-flow interference, packet delivery rate, performance analysis**

I. Introduction

Multiple relay nodes forward the packet from a source node to a destination node in wireless multi-hop networks. They can extend communication range of ad hoc networks without any communication infrastructures [1], [2]. The applications of ad hoc networks include video monitoring of natural environments to predict disasters and public space monitoring for safety. These applications exhibit higher traffic load and require higher packet delivery rate (PDR) than normal sensor applications. In order to achieve high PDR, opportunistic routing [3] and dynamic multi-hop techniques [4], [5] have been proposed. These schemes try to improve the PDR by choosing a better path for packet forwarding other than using a fixed forwarding path. In dynamic multi-hop shortcut (DMHS) [4], if a node overhears the packet transmission from a node other than its immediate preceding node, a shortcut path is established. The use of the shortcut path reduces the number of required hops compared to the network with fixed packet forwarding[1]. Since the relay node forwards the packet via either the path originally set up or the shortcut path, we obtain the path diversity gain. DMHS has been shown to be effective when the traffic load is low.

In the high traffic load applications, the packet generation interval at the source node becomes shorter. It means that the number of the relay nodes which try to forward the packet to the next relay node becomes larger. If the relay nodes are in the relationship of hidden terminal (HT) from each other, packet collision may happen. We call this collision *intra-flow interference* (*IFI*). The preceding packet hinders the establishment of the shortcut path. However, the preceding packet that causes IFI is not unknown at the node as the node has previously transmitted it. Focusing on this fact, an IFI canceller (IFIC) has been proposed in [7]. In IFIC, two packet frame formats are prepared and different formats are assigned to the nodes in the relation of HT. Each packet frame format has blank period during which the other packet frame format transmits the training sequence. This enables the node to estimate the channel coefficient of the IFI. Thus, the node is able to remove IFI. It has been shown that IFIC achieves high PDR even if packet generation interval is short [7].

To the best of authors' knowledge, the impact of IFIC in the high traffic load condition where the packet forwarding path is dynamically changed has not yet been analyzed. Since the original IFIC does not take into account the establishment of the shortcut path, we need to slightly modify its operation. We firstly derive the theoretical expression of PDR by taking into account the existence of the preceding packet in the network. Then, based on the derived PDR expression, we obtain the throughput performance. Numerical simulation will confirm its validity. Both theoretical analysis and computer simulation show the throughput improvement brought by the combination of DMHS and IFIC even under high traffic condition. Throughput performance improves about 14% when the number of hops is 8.

The remainder of this paper is organized as follows. In Section II, the system model considered in this paper is introduced and the concept of IFIC and DMHS are introduced. We provide PDR analysis in Section III. Section IV provides the numerical evaluation of the proposed DMHS+IFIC and its PDR perforamnce. Section V concludes the paper.

II. System Model

We consider a half-duplex single frequency multi-hop network with N nodes, which is indexed by $i \in \{0, 1, \cdots, N\}$. A source node 0 constantly generates a packet $v \in \{0, 1, \cdots\}$, with a fixed packet generation interval $T_{\rm int}$ (sec). Let $T_{\rm com}$ denote the time slot length required for one-hop transmission. The *normalized traffic load* is defined as $G \triangleq T_{\rm com}/T_{\rm int} \in \{1/2, 1/3, 1/4, \cdots\}$. By convention, *high traffic condition*

[1]The route can be set up by any routing protocol such as ad hoc on-demand distance vector (AODV) [6].

means $G \geq 1/3$. Packet v is generated at time slot $t_v = t_0 + (v/G)$ where t_0 denotes the time slot at which packet 0 is generated. The routing path is set up as $(0, 1, \cdots, N)$ so that the packet is forwarded from node $i-1$ to node i, and then to node $i+1$.

A. Intra-Flow Interference Canceller (IFIC)

Suppose that node i and node $i+2$ cannot carrier sense each other and they have packet v and packet $v-1$ to be transmitted, respectively. If both nodes transmit packets in the same time slot, the packet collision happens at intermediate node $i+1$. In this way, IFI is caused by a preceding packet, i.e., packet $v-1$. In order to enable IFI cancellation, two packet frame formats (PF_1 and PF_2) are prepared. Both formats have blank period at different location within a packet during which a training sequence of the other format is transmitted [7]. Suppose that nodes i and $i+1$ are assigned PF_1, whereas nodes $i+2$ and $i+3$ are assigned PF_2. Every two nodes that are in the relationship of HT, e.g., nodes i and $i+2$, use different packet frame formats. Thus, even if packet collision happens at node $i+1$, the training sequences of packet $v-1$ can be received without interference. Then, the interference is cancelled because packet $v-1$ is known interference by node $i+1$ [7].

B. Introduction of IFIC into DMHS

When a packet is transmitted from node j, $j < i-1$, node i may overhear it and correctly decode it. We call such a temporary path a *shortcut path*. However, with the conventional packet forwarding protocol, node i discards the received packet because its media access control (MAC) header does not contain the address of node i. In order to overcome this problem, DMHS employs multiple addressing which allows MAC header and routing tables to contain not only the MAC address of the next hop node but also those of several hop-ahead nodes so that the overheard packets via shortcut path is not discarded. If node i successfully overhear packet v from node j via the shortcut path, it is preferable to stop forwarding packet v from node k, $j < k < i$. Thus, node i broadcasts a stop transmitting packet (STP) to notify node k, $j < k < i$, of the packet reception at node i.

When the traffic load increases, i.e., $G \geq 1/3$, a packet collision may happen frequently due to the shorter packet generation interval T_{int}. In such a case, the opportunity for shortcut path establishment might decrease due to the transmission of preceding packet as shown in Fig. 1. In Fig. 1, node $i+2$ transmits packet $v-1$ in the same time slot as node $i-1$ transmits packet v. In such a case, even if the channel quality between node $i-1$ and node $i+1$ is good, the shortcut path cannot be created due to the packet collision. Therefore, it is necessary to introduce IFIC in order for DMHS to work in high traffic load. However, the original IFIC does not consider the shortcut path. Following the assignment procedure of packet frame format [7], nodes $i-1$ and $i+2$ are assigned the same packet frame format, i.e., PF_2. Therefore, the IFI cannot be canceled at node $i+1$. In order to let the IFIC to work under the dynamically changing packet forwarding paths, an

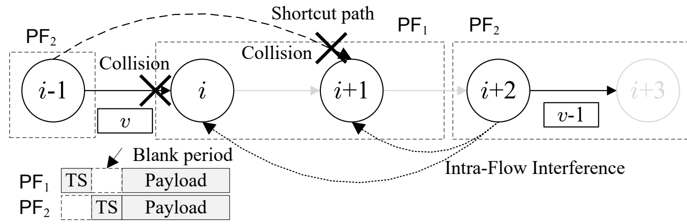

Fig. 1. Limitation of original IFIC in dynamic path forwarding.

additional packet frame format (PF_3) is introduced in this paper. Neighboring two nodes are grouped and then assigned to one of the three packet frame formats so that neighboring node groups are assigned different packet frame formats.

III. PDR Analysis

In this section, we derive the theoretical expression of PDR for the dynamic multi-hop network. Without loss of generality, the original route is denoted as $(0, 1, \cdots, i, \cdots, N)$. The interference is assumed to be perfectly cancelled if it is transmitted in a different packet format from the desired packet. Let $p_{(i,j)}$ denote the probability of successful transmission from node i to node j, which is defined as $p_{(i,j)} = 1 - \int_0^\infty P_\gamma P_{\text{e}}(\gamma) d\gamma$, where P_γ is the probability of the exponentially distributed channel gain, i.e., $\gamma \sim \exp(1)$ and $P_{\text{e}}(\gamma)$ is the packet error rate. We assume that $P_{\text{e}}(\gamma) = 0$ if γ is larger than the sensitivity level Γ and $P_{\text{e}}(\gamma) = 1$ otherwise. For notational simplicity we assume $p_{(i,i+1)} = p_{\text{o}}$ and $p_{(i,i+2)} = p_{\text{s}}$. However, the following analysis can be easily extended to the case that the channel qualities are different.

A. Low Traffic Load Condition

In the low traffic load condition, the transmission of packet v is not affected by packet $v-1$. The PDR expressions for $N = 1$ and $N = 2$ are given by $P_1^{\mathsf{L}} = p_{\text{o}}$ and $P_2^{\mathsf{L}} = p_{\text{s}} + (1 - p_{\text{s}}) p_{\text{o}}^2$, respectively. Let us next consider $N = 3$. If the shortcut path is created from node 0 to node 2, the remaining hop is one hop from node 2 to node 3. If the shortcut path is not created, the remaining hops are two hops from node 1 to node 3. Thus, the PDR expression for $N = 3$ is given by $P_3^{\mathsf{L}} = p_{\text{s}} P_1^{\mathsf{L}} + (1 - p_{\text{s}}) p_{\text{o}} P_2^{\mathsf{L}}$. Similarly, the PDR expression for any $N > 3$ can be recursively obtained as

$$P_N^{\mathsf{L}} = p_{\text{s}} P_{N-2}^{\mathsf{L}} + (1 - p_{\text{s}}) p_{\text{o}} P_{N-1}^{\mathsf{L}}. \quad (1)$$

B. High Traffic Load Condition

We consider the scenario with $G = 1/2$ but this analysis can be easily extended to $G < 1/2$. Without loss of generality, we set $t_0 = 0$. Since $G = 1/2$, a new packet is generated at the source node at every two time slots. Let l_v^t denote the location of packet v at time slot t. Let $\mathsf{Q}_N[l_v^t = i]$ denote the probability that packet v is located at node i in time slot t. Let $\mathsf{Q}_N[l_v^{t+1} = j \mid l_v^t = i]$ denote the probability that packet v is transferred from node i to node j after time slot t. Furthermore, let $\mathsf{Q}_N[l_{v-1}^t = j \mid l_v^t = i]$ denote the probability that packet $v-1$ is located at node j when packet v is located at node i

at time slot t. As long as it is clear from the context, we use $\mathsf{Q}[.]$ instead of $\mathsf{Q}_N[.]$.

1) $N = 1$ and 2: Since no packet collision happens for $N < 3$, the PDR expressions are the same as those of the low traffic environment. Thus, we have $P_1^{\mathsf{H}} = P_1^{\mathsf{L}}$ and $P_2^{\mathsf{H}} = P_2^{\mathsf{L}}$.

2) $N = 3$: If packet $v-1$ is located at node 2 when packet v is generated at node 0, packet v can not reach node 2 due to the half-duplex constraint even if the channel condition between node 0 and 2 is good. Thus, it is necessary to obtain the probability $\Pr[l_{v-1}^{t_{2v}} = 2 \mid |l_v^{t_{2v}} = 0]$. Since the location of packet $v-1$ is not affected by packet v, we have $\Pr[l_{v-1}^{t_{2v}} = 2 \mid |l_v^{t_{2v}} = 0] = \Pr[l_{v-1}^{t_{2v}} = 2]$.

We derive the PDR expression by induction. Packet 0 is located at node 2 at time slot t_2 if and only if it has not been transmitted via the shortcut path in time slot t_0 and t_1. Thus, we have $\Pr[l_0^{t_2} = 2] = (1-p_{\mathrm{s}})^2 p_{\mathrm{o}}^2$.

Similarly, the probability that packet 1 is located at node 2 when packet 2 is generated is obtained as

$$\begin{aligned}\mathsf{Q}[l_1^{t_4} = 2] &= \mathsf{Q}[l_0^{t_2} = 2] \times p_{\mathrm{o}}^2(1-p_{\mathrm{s}}) \\ &\quad + (1-\mathsf{Q}[l_0^{t_2} = 2]) \times (1-p_{\mathrm{s}})^2 p_{\mathrm{o}}^2. \end{aligned} \tag{2}$$

The probability for other packets can be obtained in the recursive manner and it converges to

$$\mathsf{Q}[l_{v-1}^{t_{2v}} = 2] = \frac{p_{\mathrm{o}}^2(1-p_{\mathrm{s}})^2}{1-p_{\mathrm{o}}^2 p_{\mathrm{s}}(1-p_{\mathrm{s}})}. \tag{3}$$

Due to the half-duplex constraint, node 2 cannot receive packet q from node 0 if packet $q-1$ is located at node 2, i.e., $l_{v-1}^{t_{2v}} = 2$. Thus, the PDR expression for $N = 3$ becomes

$$P_3^{\mathsf{H}} = \mathsf{Q}[l_{v-1}^{t_{2v}} = 2] \times p_{\mathrm{o}} P_2^{\mathsf{H}} + (1-\mathsf{Q}_3[l_{q-1}^{t_{2v}} = 2]) \times P_3^{\mathsf{L}}. \tag{4}$$

3) $N = 4$: The PDR expression for $N = 4$ can be obtained in the similar manner as for $N = 3$. However, the impact of packet $v-1$ on the transmission of packet v becomes more significant. We have $\mathsf{Q}[l_0^{t_2} = 2] = (1-p_{\mathrm{s}})^2 p_{\mathrm{o}}^2$, which is the same as that for $N = 3$. To calculate the probability that packet 1 is located at node 2 when packet 2 is generated, we need to take into account both $l_0^{t_2}$ and $l_0^{t_3}$. $\mathsf{Q}[l_1^{t_4} = 2]$ can be obtained as

$$\begin{aligned}\mathsf{Q}[l_1^{t_4} = 2] &= \mathsf{Q}[l_0^{t_2} = 2] \times p_{\mathrm{o}} \times \big\{\mathsf{Q}[l_0^{t_3} = 3 | l_0^{t_2} = 2] \times p_{\mathrm{o}} \\ &\quad + (1-\mathsf{Q}[l_0^{t_3} = 3 | l_0^{t_2} = 2]) \times (1-p_{\mathrm{s}}) p_{\mathrm{o}}\big\} \\ &\quad + (1-\mathsf{Q}[l_0^{t_2} = 2]) \times (1-p_{\mathrm{s}})^2 p_{\mathrm{o}}^2 \end{aligned} \tag{5}$$

with $\mathsf{Q}[l_0^{t_3} = 3 | l_0^{t_2} = 2] = (1-p_{\mathrm{s}})p_{\mathrm{o}}$, which is the probability that packet 0 is successfully transmitted from node 2 to node 3 when it is located at node 2 in time slot t_2.

For large v, since $\mathsf{Q}[l_{v-1}^{t_{2v}} = 2] = \mathsf{Q}[l_{v-2}^{t_{2v-2}} = 2]$, we have

$$\mathsf{Q}[l_{v-1}^{t_{2v}} = 2] = \frac{p_{\mathrm{o}}^2(1-p_{\mathrm{s}})^2}{1-p_{\mathrm{o}}^2 p_{\mathrm{s}}(1+p_{\mathrm{o}})(1-p_{\mathrm{s}})}. \tag{6}$$

Finally, the PDR expression for $N = 4$ can be obtained as

$$\begin{aligned}P_4^{\mathsf{H}} &= \\ &\mathsf{Q}[l_{v-1}^{t_{2v}} = 2] \times p_{\mathrm{o}} \times \big\{\mathsf{Q}[l_{v-1}^{t_{2v+1}} = 3 \mid l_{v-1}^{t_{2v}} = 2] \times p_{\mathrm{o}} P_2^{\mathsf{L}} \\ &+ (1-\mathsf{Q}[l_{v-1}^{t_{2v+1}} = 3 \mid l_{v-1}^{t_{2v}} = 2]) \times P_3^{\mathsf{L}}\big\} \\ &+ (1-\mathsf{Q}[l_{v-1}^{t_{2v}} = 2]) \times P_4^{\mathsf{L}}. \end{aligned} \tag{7}$$

4) $N \geq 5$: For $N = 5$, it is necessary to consider the case that packet $v-1$ is located at either node 2 or node 3 at time slot t_{2v}. Thus, in the following, we first derive the probabilities $\mathsf{Q}[l_{v-1}^{t_{2v}} = 2]$ and $\mathsf{Q}[l_{v-1}^{t_{2v}} = 3]$. Again we have $\mathsf{Q}[l_0^{t_2} = 2] = (1-p_{\mathrm{s}})^2 p_{\mathrm{o}}^2$. The probability that packet 1 is located at node 2 at time slot t_4 is given by (5). The probability that packet $v-1$ is located at node 2 at time t_{2v} is given as

$$\begin{aligned}&\mathsf{Q}[l_{v-1}^{t_{2v}} = 2] \\ &= \mathsf{Q}[l_{v-2}^{t_{2v-2}} = 2] \times p_{\mathrm{o}} \times \big\{\mathsf{Q}[l_{v-2}^{t_{2v-1}} = 3 | l_{v-2}^{t_{2v-2}} = 2] \times p_{\mathrm{o}} \\ &+ (1-\mathsf{Q}[l_{v-2}^{t_{2v-1}} = 3 | l_{v-2}^{t_{2v-2}} = 2]) \times (1-p_{\mathrm{s}}) \times p_{\mathrm{o}}\big\} \\ &+ (1-\mathsf{Q}[l_{q-2}^{t_{2q-2}} = 2]) \times (1-p_{\mathrm{s}})^2 p_{\mathrm{o}}^2. \end{aligned} \tag{8}$$

Since $\mathsf{Q}[l_{q-1}^{t_{2q}} = 2] = \mathsf{Q}[l_{q-2}^{t_{2q-2}} = 2]$ after convergence, we have

$$\mathsf{Q}[l_{q-1}^{t_{2q}} = 2] = \frac{p_{\mathrm{o}}^2(1-p_{\mathrm{s}})^2}{1-p_{\mathrm{o}}^2 p_{\mathrm{s}}(1-p_{\mathrm{s}}) \times \{1+p_{\mathrm{o}}(1+p_{\mathrm{o}}p_{\mathrm{s}})\}} \tag{9}$$

Next, we derive the probability that packet $v-1$ is located at node 3 at time t_{2v}. The probability that packet 0 is located at node 3 at time t_2 is equivalent to the probability that packet 0 arrives at node 3 via the original path and the shortcut path, thus we have $\mathsf{Q}[l_0^{t_2} = 3] = 2(1-p_{\mathrm{s}})p_{\mathrm{o}}p_{\mathrm{s}}$.

Similarly, the probability that packet 1 is located at node 3 at time t_4 is given as

$$\begin{aligned}\mathsf{Q}[l_1^{t_4} = 3] &= \mathsf{Q}[l_0^{t_2} = 2] \times p_{\mathrm{o}}p_{\mathrm{s}} \\ &\quad + (1-\mathsf{Q}[l_0^{t_2} = 2]) \times 2(1-p_{\mathrm{s}})p_{\mathrm{o}}p_{\mathrm{s}}. \end{aligned} \tag{10}$$

Since $\mathsf{Q}[l_{v-1}^{t_{2v}} = 2] = \mathsf{Q}[l_{v-2}^{t_{2v-2}} = 2]$, we have

$$\begin{aligned}\mathsf{Q}[l_{v-1}^{t_{2v}} = 3] &= \mathsf{Q}[l_{v-1}^{t_{2v}} = 2] \times p_{\mathrm{o}}p_{\mathrm{s}} \\ &\quad + (1-\mathsf{Q}[l_{v-1}^{t_{2v}} = 2]) \times 2(1-p_{\mathrm{s}})p_{\mathrm{o}}p_{\mathrm{s}}. \end{aligned} \tag{11}$$

To derive the PDR expression for $N = 5$, we need to consider the following three cases,

1) packet $v-1$ is located at node 2 at time t_{2v},
2) packet $v-1$ is located at node 3 at time t_{2v}, and
3) packet $v-1$ is located at some node other than 2 and 3.

In the case of i), packet v needs to be transferred from node 0 to node 1. If packet $v-1$ is transferred from node 2 to node 3 at time slot t_{2v}, packet v needs to be transferred from node 1 to 2 in time slot t_{2v+1}. In the case of ii), packet v can be transferred from node 0 to node 2. However, if packet $v-1$ is transferred from node 3 to node 4 at time slot t_{2v}, packet v should be transferred from node 2 to node 3 in time slot t_{2v+1}. In the case of iii), the transmission of packet v is not affected by packet $v-1$, thus it can be considered as the transmission under low traffic condition. Finally, we have the PDR expression for $N \geq 5$, which is shown at the top of the next page and

$$P_N^{\mathsf{H}} = \mathsf{Q}[l_{v-1}^{t_{2v}} = 2] \times p_{\mathrm{o}} \times \left\{ p_{\mathrm{o}} P_{N-2}^{\mathsf{L}} \mathsf{Q}[l_{v-1}^{t_{2v+1}} = 3 | l_{v-1}^{t_{2v}} = 2] + P_{N-1}^{\mathsf{L}}(1 - \mathsf{Q}[l_{v-1}^{t_{2v}} = 2]) \right\}$$
$$+\mathsf{Q}[l_{v-1}^{t_{2v}} = 3] \times \left\{ p_{\mathrm{s}} \left\{ p_{\mathrm{o}} P_{N-3}^{\mathsf{L}} \mathsf{Q}[l_{v-1}^{t_{2v+1}} = 4 | l_{v-1}^{t_{2v}} = 3] + P_{N-2}^{\mathsf{L}}(1 - \mathsf{Q}[l_{v-1}^{t_{2v+1}} = 4 | l_{v-1}^{t_{2v}} = 3]) \right\} + (1 - p_{\mathrm{s}}) p_{\mathrm{o}} P_{N-1}^{\mathsf{L}} \right\}$$
$$+P_N^{\mathsf{L}} \times (1 - \mathsf{Q}[l_{v-1}^{t_{2v}} = 2] - \mathsf{Q}[l_{v-1}^{t_{2v}} = 3]), \tag{12}$$

$$\begin{cases} \mathsf{Q}[l_{v-1}^{t_{2v+1}} = 3 | l_{v-1}^{t_{2v}} = 2] = p_{\mathrm{o}}(1 - p_{\mathrm{s}})(1 + p_{\mathrm{o}} p_{\mathrm{s}}) \\ \mathsf{Q}[l_{v-1}^{t_{2v+1}} = 4 | l_{v-1}^{t_{2v}} = 3] = p_{\mathrm{o}}(1 - p_{\mathrm{s}}) \\ \mathsf{Q}[l_{v-1}^{t_{2v}} = 2] = \frac{p_{\mathrm{o}}^2 (1 - p_{\mathrm{s}})^2}{1 - p_{\mathrm{o}}^2 p_{\mathrm{s}} (1 - p_{\mathrm{s}}) \times \{1 + p_{\mathrm{o}}(1 + p_{\mathrm{o}} p_{\mathrm{s}})\}} \\ \mathsf{Q}[l_{v-1}^{t_{2v}} = 3] \\ = \mathsf{Q}[l_{v-1}^{t_{2v}} = 2] \times p_{\mathrm{o}} p_{\mathrm{s}} (1 - \mathsf{Q}[l_{v-1}^{t_{2v}} = 3 | l_{v-1}^{t_{2v}} = 2]) \\ \qquad + (1 - \mathsf{Q}[l_{v-1}^{t_{2v}} = 2]) \times 2 p_{\mathrm{o}} p_{\mathrm{s}} (1 - p_{\mathrm{s}}) \end{cases} . \tag{13}$$

For $N > 6$, the number of the scenarios we need to take into account increases, we use the same expression as for $N = 5$. Although the expression is approximate for $N > 6$, we validate its accuracy via computer simulation in Sect. IV.

IV. Numerical Evaluation

A. Throughput Calculation

The throughput is calculated by $T = \frac{8B \times P_N^{\mathsf{H}}}{T_{\mathrm{com}}^{\mathrm{i}}/G}$ where B is the payload size (Bytes), P_N^{H} is the PDR derived in Sect. III, and $T_{\mathrm{com}}^{\mathrm{i}}$, $\mathrm{i} \in \{\mathrm{CSMA/CA}, \mathrm{DMHS}, \mathrm{IFIC}, \mathrm{DMHS/IFIC}\}$, is the average required time for one-hop transmission of each scheme which will be derived in the following. The explanation of each variable is given in Table I.

1) CSMA/CA: For the fixed routing scheme, we have $T_{\mathrm{com}}^{\mathrm{CSMA/CA}} = T_{\mathrm{DATA}} + T_{\mathrm{ACK}} + \frac{W_{\mathrm{CNT}} \times T_{\mathrm{slot}}}{2} + T_{\mathrm{DIFS}} + T_{\mathrm{SIFS}}$.

2) DMHS: When a shortcut path is created, STP transmission time is necessary in addition to the average path packet delivery time of fixed routing scheme. STP transmission time can be the same length of ACK packet. However, since shortcut does not always occur, the average one-hop packet transmission time for DMHS is approximated to that of the fixed packet forwarding, i.e., $T_{\mathrm{com}}^{\mathrm{DMHS}} = T_{\mathrm{com}}^{\mathrm{CSMA/CA}}$.

3) IFIC: Since multiple nodes can concurrently transmit packets, MAC protocol other than CSMA/CA can be adopted. In this paper, we adopt the MAC protocol in [7]. The average transmission time for one-hop transmission of IFIC is obtained as $T_{\mathrm{com}}^{\mathrm{IFIC}} = T_{\mathrm{TS}} + T_{\mathrm{PL}} + T_{\mathrm{ACK}}' + T_{\mathrm{BLANK}} + T_{\mathrm{SIFS}}$.

4) DMHS + IFIC: Since one more packet frame format is introduced, the additional blank time is required, thus we have $T_{\mathrm{com}}^{\mathrm{DMHS/IFIC}} = T_{\mathrm{com}}^{\mathrm{IFIC}} + T_{\mathrm{BLANK}} + T_{\mathrm{STP}} + T_{\mathrm{SIFS}}$.

B. Performance Evaluation

The radio parameters follow IEEE 802.11g and ITU-R P.1411-7 UHF Model-median [8] is adopted for propagation model. We set $G = 1/2$. The average required time for one-hop transmission of each scheme with the parameters in Table I is given in Table II. The node layout is shown in Fig. 2.

TABLE I
Radio Parameters

Parameter	Variable	Value
Data frame length	T_{DATA}	536 μsec
ACK frame length	T_{ACK}	28 μsec
DIFS duration	T_{DIFS}	34 μsec
SIFS duration	T_{SIFS}	16 μsec
Initial contention window size	W_{CNT}	15
Slot duration	T_{slot}	9 μsec
Payload length	T_{PL}	512 μsec
Training sequence length	T_{TS}	20 μsec
Blank time for IFIC	T_{BLANK}	30 μsec
ACK frame length for IFIC	T_{ACK}'	8 μsec
STP transmission length	T_{STP}	28 μsec
Payload size	B	1,500 bytes

TABLE II
Average Transmission Length

	$T_{\mathrm{com}}^{\mathrm{CSMA/CA}}$	$T_{\mathrm{com}}^{\mathrm{DMHS}}$	$T_{\mathrm{com}}^{\mathrm{IFIC}}$	$T_{\mathrm{com}}^{\mathrm{DMHS/IFIC}}$
Time	682 μsec	682 μsec	586 μsec	660 μsec

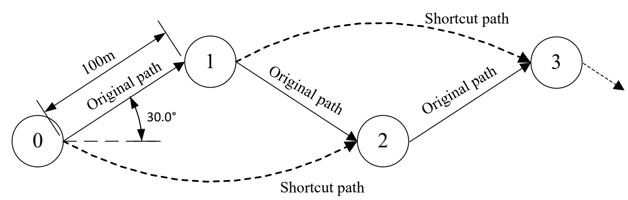

Fig. 2. Node layout.

Fig. 3 shows the PDR of four schemes. The proposed DMHS-IFIC and IFIC w/ fixed routing were evaluated by both theoretical calculations developed in Sec. III and computer simulations, whereas DMHS and the fixed routing were evaluated only by computer simulations. Theoretical calculation results are shown by solid lines and simulated results are shown by plots. The figure shows that PDR of CSMA/CA significantly degrades due to IFI [7]. Comparing with the fixed path forwarding scheme, DMHS significantly improves the PDR performance for small N. This is because shortcut paths reduce the hop count and hence the opportunity that IFI occurs is reduced. However, PDR drops rapidly when N is larger than four. Since IFI can be effectively suppressed by IFIC, higher PDR is obtained by IFIC with fixed path forwarding compared to fixed path forwarding and DMHS. However, since no shortcut path is created, the required hop count is always N. The proppsed DMHS-IFIC can achieve the PDR performance more than 90% irrespective of the number of hops N. Furthermore, Fig. 3 shows the theoretical value obtained from the analytical expression derivation in Sect. III quite well

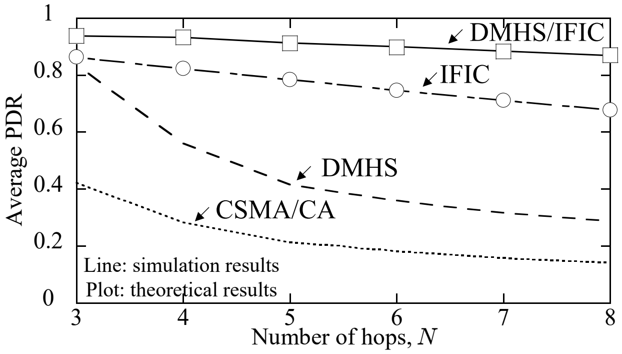

Fig. 3. PDR performance.

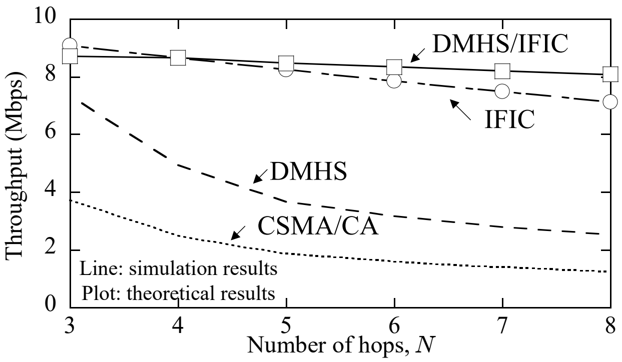

Fig. 4. Throughput performance.

agrees with that obtained by computer simulation up to $N = 8$, which is sufficient for general multihop applications.

The throughput performance of each scheme is shown in Fig. 4, where lines show the numerical results and the plots show the theoretical results obtained in Sec. III. Fig. 4 clearly shows the theoretical results and the numerical results well agree with each other even for large N, i.e., $N > 5$. This confirms the validity of the theoretical expression. Fig. 4 shows that as the number of hops N increases, the throughput performances of CSMA/CA and DMHS w/ CSMA/CA significantly degrade due to the IFI. By introducing DMHS and IFIC into the system, the throughput significantly increases. This is due to the path diversity obtained by DMHS and the effective cancellation of IFI. Although $T_{\rm com}^{\rm DMHS/IFIC} > T_{\rm com}^{\rm IFIC}$, the throughput performance of DMHS/IFIC is higher than that of IFIC only, e.g., about 14% improvement when $N = 8$. This result indicates that the combination of DMHS and IFIC is quite effective to increase the throughput performance when the number of hops is large.

V. Conclusion

This paper provided the theoretical analysis for the throughput performance of dynamic multi-hop networks under high traffic load condition. We have introduced IFIC in order to increase the number of the shortcut path establishments. Computer simulation results have validated the theoretical expression. Both the simulation results and the theoretical analysis have confirmed the throughput improvement brought by the introduction of DMHS and IFIC into the system. It has been shown that the throughput performance improves about 14% when the number of hops is 8.

Interesting future works include the analysis of the establishment of the shortcut path and the optimization of the number of packet frame formats in the general node layout.

References

[1] E. Royer and C. Toh, "A review of current routing protocols for ad hoc mobile wireless networks," *IEEE Personal Commun. Mag.,* vol. 6, pp. 46-55, Apr. 1999.

[2] C. Murthy and B. Manoj, *Ad Hoc Wireless Networks -Architectures and protocols-*. Englewood Cliffs, NJ: Prentice Hall, 2004.

[3] S. Biswas and R. Morris, "Opportunistic routing in multi-hop wireless networks," *ACM SIGCOMM Computer Communication Review*, vol. 34, no. 1, pp. 69-74, Jan. 2004.

[4] Y. Yamao, Y. Kadowaki, and K. Nagao, "Dynamic multi-hopping for efficient and reliable transmission in wireless ad hoc networks," *in Proc. APCC 2008*, Tokyo, Japan, Oct. 2008, pp. 1-4.

[5] Y. Matsuzawa, Y. Yamao, K. Otake, and K. Ishibashi, "Multi-hop transmission performance of integrated dynamic multihopping for wireless ad hoc networks," *in 11th IEEE CCNC 2014*, Las Vegas, USA, Jan. 2014.

[6] C. Perkins and E. Royer, "Ad-hoc on demand distance vector routing," *in The 2nd IEEE Workshop on Mobile Computing Systems and Applications*, New Orleans, USA, Feb. 1990, pp. 1-11.

[7] J. Dai, K. Ishibashi, and Y. Yamao, "Highly efficient multi-hop packet transmission using intra-flow interference cancellation and maximal ratio combining," *IEEE Trans. Wireless Commun.*, vol. 14, no. 11, pp. 5998-6011, Nov. 2015.

[8] "Propagation data and prediction methods for the planning of short-range outdoor radio communication systems and radio local area networks in the frequency range 300 MHz to 100 GHz," ITU-R, Tech. Rep. P.1411-7, 2013.