LETTER

Throughput Improvement in Wireless Multi-Hop Ad-Hoc Networks Using Load Control

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SUMMARY IEEE 802.11 MAC is the most commonly used protocol in multi-hop ad-hoc networks which need no infrastructure. In multi-hop ad-hoc networks based on IEEE 802.11, since nodes try transmitting their packets at every possible slot, there is a high packet loss probability. This degrades network performance attributes such as throughput and fairness. In this paper, we focus on achieving the maximum throughput of the given network topology by adding extra backoff time to random backoff time based on IEEE 802.11. Specifically, the optimal load rate is obtained with constraints of Carrier Sensing Multiple Access/ Collision Avoidance (CSMA/CA) mechanism.

key words: ad-hoc, load control, throughput, 802.11 MAC

1. Introduction

Ad-hoc networks which need no infrastructure can be used in the situations in which temporary network services are required or installation of cables is difficult. IEEE 802.11 MAC Distributed Coordination Function (DCF) based on Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) is the most commonly used medium access protocol in multi-hop ad-hoc networks. Performance of IEEE 802.11 DCF is analyzed using the transmission probability at a randomly chosen slot and the maximum throughput is achieved by adjusting the contention window size (CW) according to the number of nodes under the single-hop environment [2], [3]. However, we cannot adopt these results directly in multi-hop networks due to existence of hidden nodes. They may cause a high collision probability in multi-hop ad-hoc networks. The high collision probability causes performance attributes such as throughput and fairness to be degraded [4], [6]. There are many researches to solve problems such as throughput degradation and unfairness in multi-hop networks. In [9], the authors suggest the optimum packet scheduling for each traffic flow (OPET) to improve performance in ad hoc networks by introducing the back-pressure scheme. However, the extra bit in the RTS/CTS format is needed to implement. In [5], [7], [8], the authors use the concept of the load rate of nodes to analyze the throughput under the assumptions that each node has the same load rate and the equal collision probability. Specially in [5], [7], the authors focus on analyzing the collision probability by the function of the load rate in multi-hop networks. In [8], the authors suggest the complementary backoff algorithm (CBA) to achieve the maximum throughput under the infinite linear chain topology but the control scheme is not easily extendable to general multi-hop networks.

In this paper, to achieve the maximum throughput in general multi-hop networks, we use the load rate of nodes without an assumption of the same load rate at each node. We analyze the load rate of each node to achieve the maximum throughput with constraints from CSMA/CA mechanism. Then, we suggest the proper additional backoff time as a control parameter so that we can achieve the maximum throughput. We apply our control scheme to the linear chain topology and the lattice topology, validate the control scheme through simulations and compare the control scheme with IEEE 802.11 and OPET.

2. Load Rate

In this section, we estimate the optimal rate at which the throughput of the given network topology is maximized by using the optimization technique. First of all, consider an ad-hoc network with \( N \) nodes and a set \( L = \{ L_i | i = 1, 2, \cdots, L \} \) of links with cardinality \( L \). Then, define an \( L \times N \) matrix \( R \). The matrix \( R \) has the information of node’s characteristics such as a source node and a sink node of each link. The element \( r_{ij} \) of \( R \) is

\[
r_{ij} = \begin{cases} 
1, & \text{if node } j \text{ is on the link } L_i \text{ and node } j \text{ transmits packets through } L_i \\
-1, & \text{if node } j \text{ is on the link } L_i \text{ and node } j \text{ receives packets through } L_i \text{ as a relay node} \\
0, & \text{otherwise} 
\end{cases}
\]

The row index corresponds to the link between two nodes. The column index corresponds to nodes of the network. Specifically, element \( r_{ij} \) that equals 1 means node \( j \) transmits packets as a source node of link \( i \). Element \( r_{ij} \) that equals −1 means node \( j \) receives packets from another node connected to link \( i \). To represent the throughput of a node, we use the average load rate \( x_i \) of node \( i \) during the total time duration \( T \). Thus, \( x_i = Q_i / T \) where \( Q_i = t_4 - t_5 + t_7 - t_1 \) is the occupied channel time duration of node \( i \) during \( T \). It consists of PHY Header, MAC Header, Payload, Distributed Interframe Space (DIFS), Short Interframe Space (SIFS), and
Acknowledge (ACK) time in case of successful transmission or ACK time-out in the case of collision, respectively as shown in Fig. 1. In our analysis, we assume both cases have the equal time duration of transmission for simplicity. Then, by introducing the collision probability \( q_i \) of node \( i \), the throughput of node \( i \) is \( T_{hi} = x_i \cdot (1 - q_i) \cdot a \cdot \text{datarate} \) where \( a \) means the payload data fraction of successful transmission such that

\[
a = \frac{\text{Payload}}{\text{PHY+MAC+Payload+SIFS+DIFS+ACK}}
\]

In wireless networks, due to interference with other transmissions, collisions have occurred if two or more transmissions are overlayed. Thus, the sum of load rates inside the carrier sensing range of node \( i \) greater than 1 means that there is at least one collision. Moreover, each node experiences a random backoff time chosen in \((0, CW)\) before transmission. Considering backoff time at each node, we know that the sum of the load rates has to be lower than 1 and given as \( E[P]/(E[P] + E[CW]) \) where \( E[-] \) and \( P \) means the expected value and time duration of each transmission, respectively. In multi-hop, there may exist the nodes that can transmit at the same time without collisions. As shown in Fig. 2, consider a linear chain topology with 2 hop distance interference range and 1 hop distance transmission range. Although node 3 can sense transmission of node 1 and node 5, node 1 and node 5 can transmit their packets at the same instance. Also, node 2 and node 6 can do. The maximum load rate without collision is increased by the common time duration of them. Then, we can define a set \( M_i = \{ M_j \mid M_j \text{ is a set of the load rate of nodes that can transmit at the same time without collision inside the carrier sensing range of node } i \} \). Considering the multi-hop environment, we can set the optimization problem through the function \( U(x_i) \) representing the throughput at node \( i \) as below:

\[
\begin{align*}
\text{max} & \sum_{x_i} U(x_i) \\
\text{subject to} & \sum_{x_i \in M_i} x_i \leq \frac{E[P]}{E[P] + E[CW]} + \min(M_j), \text{ for all } j \\
\text{and} & \textbf{Rx} \geq 0, \quad x = [x_1, x_2, \ldots, x_n]^T
\end{align*}
\]

where \( C_j \) and \( S \) mean a set of the nodes inside the carrier sensing range of node \( j \) and a set of sink nodes. If node \( j \) operates as a relay node of its source node \( i \), \( x_i \) should be less than \( x_j \), hence we add \( \textbf{Rx} \geq 0 \) as a constraint. To solve this optimization problem and obtain the achievable throughput, we have to know the throughput function \( U \) explicitly. It is not easy to obtain the explicit \( U \) under the multi-hop environment. Since the constraints we choose mean that nodes inside the carrier sensing range do not overlay at any instant, if there exists a scheduling scheme that distributes the load rate, the throughput function \( U \) of node \( i \) is only dependent on its own node and has a form of \( x_i \cdot a \cdot \text{datarate} \). Moreover, since the throughput function \( U(x_i) \) is a strictly increasing function, \( x_i \) should have the maximum value to maximize \( U(x_i) \). Thus, the load rate at each node in the same flow is equal. Moreover, only the strongest constraint at each flow remains. Thus, the above optimization problem can be rewritten as below:

\[
\begin{align*}
\text{max} & \sum_{x_i} U(x_i) \\
\text{subject to} & \sum_{x_i} \alpha_i x_i \leq \frac{E[P]}{E[P] + E[CW]} \text{ for all flows}
\end{align*}
\]

where \( \alpha_i \) is an integer value from the strongest constraint at each flow.

### 3. Control Scheme

From the previous section, we have obtained the load rates to maximize the end-to-end throughput. To obtain the maximum end-to-end throughput, we introduce the extra backoff time that makes node \( i \) have the optimal load rate obtained by (3). Nodes experience four states from one transmission to the next transmission.

1. transmission state: a node is transmitting.
2. back-off state: a back off timer decreases by one.
3. freezing state: a back off timer is frozen due to other transmission inside the carrier sensing range.
4. Empty state: a node has no packet to transmit.

Then, let \( \alpha_i, \beta_i, \gamma_i, \) and \( I_i \) be the time duration of each state. Thus, the total time duration \( G_i \) per transmission can be represented by the sum of time slots of each state. Since \( \beta_i \) is equal to the backoff time approximately, we can obtain the backoff time

\[
\beta_i = G_i - (\alpha_i + \gamma_i + I_i)
\]

Since \( \alpha_i \) is equal to the average packet size and \( I_i \) can be
measured at each node, we only estimate \( G_i \) and \( \gamma_i \). To estimate these parameters, define \( n_i \) as the number of transmissions of node \( i \) and \( n_{ci} \) as the total number of transmission inside the carrier sensing range of node \( i \) during \( T \). Then, \( G_i \) has the following relation

\[
G_i = \frac{T}{n_i} = \frac{E[P]}{x_i}
\]

(5)

To estimate \( \gamma_i \), we have to know the relation between the number of transmission of node \( i \) and the number of transmission of nodes inside the carrier sensing range of node \( i \). This relation can be obtained from the definition of load rate and (5).

\[
\frac{(n_{ci} - n_i)E[P]}{T} = \sum_{j \in C_i \setminus \{i\}} x_j
\]

(6)

\[
\gamma_i = \frac{(n_{ci} - n_i)E[P]}{n_i} = \sum_{j \in C_i \setminus \{i\}} \frac{x_j}{x_i} E[P]
\]

(7)

where \( C_i \setminus \{i\} \) is the difference of sets between \( C_i \) and \( \{i\} \). By substituting (5) and (7) into (4), we determine the backoff time that node \( i \) has to experience before transmitting a packet as below:

\[
\text{Backoff}_i = \left[ G_i \left( \frac{\sum_{j \in C_i \setminus \{i\}} x_j}{x_i} + 1 \right) E[P] - I \right]^+
\]

(8)

where \( [x]^+ = \max\{x, 0\} \).

## 4. Simulations

To validate the control scheme, we compare two scenarios: linear chain topology and lattice topology. These scenarios are simulated by the MATLAB program that closely follows the IEEE 802.11 protocol at each node under the assumption that the only first node of each flow generates packets. The parameters used in the simulation are summarized in Table 1. According to these parameters, time duration of each transmission is \( P = \frac{184+128+272+240}{180} \times 50 \mu s + 50 \mu s = 179.60 \) ms. However, since \( P \) should take an integer value, we set \( P = 180 \) (slots) and constant \( a = \frac{184+128+272+240}{180} = 0.909 \).

### 4.1 Linear Chain

Let’s consider the 7-hop linear chain topology shown in Fig. 2. The optimal load rate \( x^* \) can be obtained from (3) with the assumption of \( E[CW] = 32 \). The optimal load rate \( x^*_i = 0.2122 \) for all \( i \) and the maximum throughput is 193 kbit/s = 0.2122 \cdot a \cdot 1 \text{ Mbit/s}. Simulation results are shown in Figs. 3 and 4. In Fig. 4, higher load rates of node 1-3 than the optimal rate 0.2122 result in degradation of throughput. Because nodes which have larger than the optimal rates have more occupation of the channel and prevent from accessing the channel of other relay nodes. Thus, when all nodes of the same flow have the same load rate, the end-to-end throughput is maximized. With the control scheme, the load rate per node has the same value 0.2122 regardless of the offered input traffic as shown in Fig. 4 and the proposed method offers the improved end-to-end throughput than the other algorithms.

### 4.2 Lattice Topology

Consider an M by N lattice topology in Fig. 5. In our simulation, for convenience, we set \( M \) and \( N \) as 4 and 5, respectively. From (3), the optimal load rate of each node and the maximum throughput can be achieved. The maxi-

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**Table 1. Simulation parameter.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet size</td>
<td>8184 bit</td>
</tr>
<tr>
<td>PHY header</td>
<td>128 bit</td>
</tr>
<tr>
<td>MAC header</td>
<td>272 bit</td>
</tr>
<tr>
<td>ACK</td>
<td>112 bit + PHY header</td>
</tr>
<tr>
<td>Channel bit rate</td>
<td>1 Mbit/s</td>
</tr>
<tr>
<td>Slot Time</td>
<td>50 ( \mu )s</td>
</tr>
<tr>
<td>SIFS</td>
<td>28 ( \mu )s</td>
</tr>
<tr>
<td>DIFS</td>
<td>128 ( \mu )s</td>
</tr>
<tr>
<td>( CW_{min} )</td>
<td>32</td>
</tr>
<tr>
<td>( CW_{max} )</td>
<td>1024</td>
</tr>
<tr>
<td>Retransmission limit</td>
<td>7</td>
</tr>
<tr>
<td>Transmission range</td>
<td>1-hop distance</td>
</tr>
<tr>
<td>Carrier sensing range</td>
<td>2-hop distance</td>
</tr>
<tr>
<td>Simulation time</td>
<td>300 sec</td>
</tr>
</tbody>
</table>

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**Fig. 3** End to end throughput in 7 hop chain.

**Fig. 4** Load rate and throughput at each node on 409 kbps.
mized aggregate throughput is achieved when the first flow and the fourth flow share the total time duration. This result is so obvious because the first flow and the fourth flow can transmit without collisions at any instant. However, because of fairness, we have to consider transmission time of the second flow and the third flow. Figures 6(a), (b), (c) show that the end-to-end throughput of each flow. The edge flows have the higher end-to-end throughput than the middle flows. Because the edge flows experience less competition than the middle flows. In the case of the control scheme shown in Fig. 6(c), all 4 flows have the almost same end-to-end throughput close to the analytical results in Table 2.

5. Conclusion

In this paper, we have obtained the optimal load rate that maximizes the end-to-end throughput at the given multi-hop wireless network and propose a control scheme by adding the extra backoff time at each node. We use the optimization technique to find the optimal load rate based on the strictly increasing throughput function with constraints of IEEE 802.11 CSMA/CA mechanism. Simulations showed that the proposed scheme offers improved accuracy and throughput. Furthermore, the proposed control scheme can be adopted in general multi hop networks.

References


