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Delay Analysis for IEEE802.11 Multi-hop Networks Taking Into Account the Concurrent-Transmission Collisions

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Abstract—This paper presents analytical expressions of throughput, collision probability, frame existence probability, and end-to-end delay for the IEEE 802.11 Distributed Coordination Function (DCF) protocol in wireless multi-hop networks with one-way flow under unsaturated traffic loads. The hidden-node collisions and concurrent-transmission collisions are considered in this paper. First, analytical expressions of transmission airtime, collision probability, throughput and frame existence probability are derived. By using these expressions and buffer-state transition model, analytical expressions of end-to-end delay can be obtained. The validities of the analytical expressions are confirmed from the quantitative agreements between the analytical and simulation results.

1. Introduction

Due to the rapid growth of the ubiquity of IEEE 802.11 MAC for wireless multi-hop networks, it is necessary and effective to comprehend the multi-hop network dynamics in detail. It is an important and challenging problem to obtain the general analytical expressions of network performance, such as throughput, collision probability, and end-to-end delay.

Because wireless multi-hop networks show complex dynamics, each node should be considered independently in multi-hop network [1]. Reference [2] provides the delay analysis of the IEEE 802.11 in multi-hop networks with saturated conditions. In [3], delay analysis was carried out in multi-hop networks with non-saturated traffic. Both [2]and [3] assumed all nodes are in the transmission range one another. Therefore, identical transmission and collision probabilities of each node can be assumed. In wireless multi-hop network, however, hidden-node problem is a serious problem, transmission and collision probabilities of a certain node should be different from influence of other nodes. Therefore, analytical approaches in both [2]and [3] cannot be extended to the multi-hop networks analysis with hidden-node problem. On the other hand, references [1] and [4] present the analytical expressions of the maximum throughput for multi-hop networks with hidden-node problem. [1] assumed each node has different transmission and collision probabilities in multi-hop networks, which can be extended to delay analysis for multi-hop networks with hidden-node problem. However, in [1], the collisions caused by concurrent-transmission are not considered.

This paper presents analytical expressions of throughput, collision probability, frame existence probability, and end-to-end delay for the IEEE 802.11 Distributed Coordination Function (DCF) protocol in wireless multi-hop networks with one-way flow under unsaturated traffic loads. The hidden-node collisions and concurrent-transmission collisions are considered in this paper. First, analytical expressions of transmission airtime, collision probability, throughput and frame existence probability are derived. By using these expressions and buffer-state transition model, analytical expressions of end-to-end delay can be obtained. The validities of the analytical expressions are confirmed from the quantitative agreements between the analytical and simulation results.

2. Analytical expression of end-to-end delay of wireless multi-hop networks

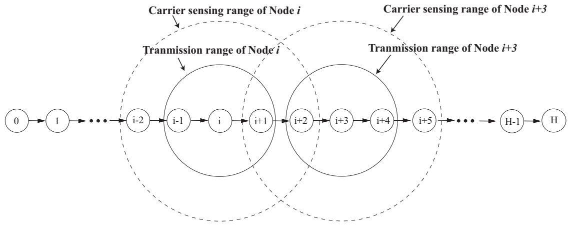

Figure 1: Network topology used for analysis and simulation

In this analysis, end-to-end delay of IEEE 802.11 wireless multi-hop networks is derived. In this analysis, H-hop string topology with one-way flow as shown in Fig. 1, is considered. The present analysis based the following assumption:

1. Node 0 generates transmission frames, whose destination is Node H.
2. Generated frames by Node 0 are relayed via Node 1 to Node H.
3. The relay nodes never generate transmission frames by themselves.

4. Carrier-sensing distance is twice as long as transmission distance. Additionally, Node i and Node $(i + 3)$ are in hidden-node relationship.
5. Frame collisions induced by hidden nodes and concurrent-transmission of the same carrier-sensing nodes are considered.
6. Frames drop are not considered in this model.

2.1. Modeling of IEEE802 .11 Wireless Multi-hop Networks in Non-saturated State

The enough long time interval $[0, Time]$ is considered. The transmission airtime of Node i is expressed as

$$x_i = \lim_{Time\to\infty} \frac{|S_i|}{Time}, \tag{1}$$

where S_i is the transmission airtime within this interval that Node i transmits, let $|S_i|$ be the length of this interval. This airtime includes transmission time of data frames(FRAME), acknowledgement frames from the receiving node(ACK), the durations of the distributed interframe space(DIFS) and the short interframe space(SIFS).

By using (1), the expression of throughput for Node i is

$$E_i = x_i \times (1 - \gamma_i) \times \frac{payload}{T} \times datarate. \tag{2}$$

In (2), γ_i is the collision probability of Node i, and $T = DIFS + FRAME + SIFS + ACK$, where $DIFS$ is the duration of the DIFS, $FRAME$ is the transmission time of the FRAME, $SIFS$ is the duration of the SIFS, ACK is the transmission time of the ACK, and $payload$ is the payload of data frame.

The carrier sensing airtime of Node i is total transmission airtimes of the neighbor nodes, so the carrier sensing airtime is represented as

$$y_i = \sum_{j\in v(i)} x_j - \sum_{m\notin v(n)\cup n;m,n\in v(i)} \frac{x_m x_n}{1-\sum x_c}, \quad \text{for } c \in \theta(m,n), \tag{3}$$

where $v(i)$ is the sets of neighbor nodes of Node i, $\theta(m, n)$ is the set of the nodes in the transmission range of both Node m and Node n.

The idle airtime is defined as z_i. In non-saturated state, the idle airtime consists of not only the expended time of the backoff-time decrement, but also the duration when the node has no transmission frame in buffer[1]. In other words, the idle airtime is the time that a node is not in both transmission and carrier sensing states. Therefore, we have The idle airtime of Node i is expressed as

$$z_i = 1 - x_i - y_i. \tag{4}$$

The frame existence probability q_i, which is the probability that Node i has at least one frame during the idle state [1]. $q_i z_i$ express as the expanded airtime for the backoff-time decrement. Therefore, we have

$$q_i z_i = \frac{E_{i-1} \times \sigma \times V(\gamma_i)}{payload}, \tag{5}$$

where $V(\gamma_i) = b_0 + \gamma_i b_1 + \gamma_i^2 b_2 + \cdots + \gamma_i^P b_P$, b_P is the average backoff number in Pth transmission, σ is the time length of one slot. In IEEE 802.11a standardization, $\sigma = 9\ \mu s$ and $b_0 = 8$. q_i can be expressed as

$$q_i = \min\left(\frac{E_{i-1} \times \sigma \times V(\gamma_i)}{payload \times z_i}, 1\right). \tag{6}$$

Q_i is the probability that Node i has at least one frame in the transmission buffer in the duration of $[0, Time]$. It is assumed in this analysis that the probabilities that at least one frame exists in carrier-sensing state are the same as those in idle state. Therefore, Q_i can be expressed as

$$Q_i = x_i + q_i(1 - x_i). \tag{7}$$

By using (7), it is possible to obtain the analytical expression of end-to-end delay, which is described in Section 2.2.

In this analysis, collisions are caused by hidden-node problem or concurrent-transmission. Therefore, the collision probability of Node i is expressed as

$$\gamma_i = \gamma_i^{hid} + \gamma_i^{con}, \tag{8}$$

where γ_i^{hid} is the collision probability induced by hidden nodes. There are two types of the hidden-node collisions. When Node i starts to transmit a frame during the Node-$i + 3$ data-frame transmission, the Node-i frame is collided with the Node-$i + 3$ frame. This type of the collision is called as protocol-hidden-node collision [4]. Protocol-hidden-node-collision probability is expressed as

$$\gamma_i^{pro} = \frac{a x_{i+3}}{1 - x_{i+1} - x_{i+2}}, \tag{9}$$

where $a = FRAME/T$. DATA-ACK and ACK-ACK collisions are ignored in this paper. Similarly, when Node $i+3$ starts to transmit a frame during the Node-i transmission, the frame collisions also occur between Nodes i and $i+3$. This type of the collision is called as physical-hidden-node collision [4]. Physical-hidden-node-collision probability can be obtained as

$$\gamma_i^{phy} = \frac{a x_i}{1 - x_{i+1} - x_{i+2}}. \tag{10}$$

Because the protocol hidden-node and the physical hidden-node collisions are independent events, γ_i^{hid} is

$$\gamma_i^{hid} = \gamma_i^{pro} + \gamma_i^{phy}. \tag{11}$$

In addition, γ_i^{con} in (8) is the concurrent-transmission collision probability induced by the carrier-sensing node transmission, which is expressed as

$$\gamma_i^{con} = 1 - \prod_{j\neq i}(1 - G_j), \text{for} j \in v(i), \tag{12}$$

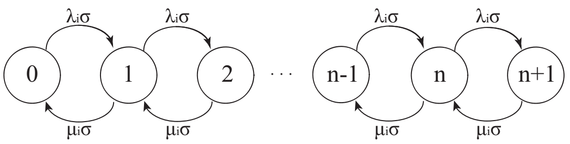

Figure 2: Buffer state transition

where G_j is the attempt rate of carrier-sensing node.

Attempt rate G_i is the probability of Node i attempt to transmit frames. Every time when backoff timer of node i decrements to 0, node i will attempt to transmit frame. Therefore, the attempt rate of Node i can be expressed as

$$G_i = \frac{1 + \gamma_i + \gamma_i^2 + \cdots + \gamma_i^P}{b_0 + \gamma_i b_1 + \gamma_i^2 b_2 + \cdots + \gamma_i^P b_P} \times q_i \times z_i. \tag{13}$$

In unsaturated throughput case, all nodes in the string-topology network relay the frame without frame drop, there is no bottleneck node in the network flow. Therefore, end-to-end throughput is the same as the offered load. Network with unsaturated traffic satisfies the "flow constraint" [1], which is expressed as

$$offeredload = E_0 = E_1 = \cdots = E_{H-1}. \tag{14}$$

From (2), (8) and (14), H algebraic equations are obtained with $3H$ unknown variations, which are $x_0, x_1, \cdots, x_{H-1}, \gamma_0, \gamma_1, \cdots, \gamma_{H-1}, E_0, E_1, \cdots, E_{H-1}$. These unknown values can be obtained by solving the algebraic equations numerically. In this paper, the Newtons method is applied for solving the algebraic equations. Therefore, we can obtain transmission airtimes and collision probabilities for all the nodes by solving (14), furthermore, carrier-sensing airtime, idle airtime, collision probability and frame existence probability are also can be obtained from the transmission airtime and collision probability.

2.2. Delay Analysis

In string multi-hop networks, the end-to-end delay is time cost that a frame is transmitted from source node to destination node. From perspective of Node i, the single-hop transmission delay consists of two parts: the queuing delay D_i^{que} and the MAC access delay D_i^{mac}. In order to obtain D_i^{que}, the buffer state transition of Node i is considered in this model.

2.2.1. Buffer State Transition

The buffer state transition model of Node i as shown in Fig. 2. λ_i is the frame arrival rate and μ_i is the frame service rate. Let p_n be the state probability that buffer has n frames, p_n can be expressed as

$$p_n(i) = \left(\frac{\lambda_i}{\mu_i}\right)^n p_0(i), n = 0, 1, 2 \cdots. \tag{15}$$

The sum of state probability should satisfy

$$\sum_{n=0}^{\infty} p_n(i) = 1, n = 0, 1, 2 \cdots. \tag{16}$$

p_0 express the probability that buffer has 0 frame, as same definition as $1 - Q_i$, therefore, we have

$$p_0(i) = 1 - Q_i. \tag{17}$$

From (15), (16) and (17), p_n can be expressed as

$$p_n(i) = Q_i^n (1 - Q_i), n = 0, 1, 2 \cdots. \tag{18}$$

2.2.2. Delay Analytical Expressions

D_i^{que}, the queuing delay of Node i is expressed as

$$D_i^{que} = \frac{payload}{E_{i-1}} \left(\frac{1}{2} \sum_{n=2}^{\infty} p_n(i) + \sum_{n=3}^{\infty} (n-2) p_n(i) \right), \tag{19}$$

where $\frac{payload}{E_{i-1}}$ expresses the inter-frame time of Node i. The right-hand side of (19) expresses spending time from when a frame arrives at Node i to when the frame reaches to the top of the buffer of Node i. The first term of the right-hand side means the expected waiting time from when a frame arrives a node to when the frame raises one up of the buffer. From (14) and (18), the queuing delay can be written as

$$D_i^{que} = \frac{payload}{offeredload} \frac{Q_i^2 + Q_i^3}{2(1 - Q_i)}. \tag{20}$$

Node i can be one of three potential states in transmission processing, namely transmission state, carrier sensing state and idle state. Therefore, the MAC access delay of Node i can be expressed as

$$D_i^{mac} = \frac{payload}{offeredload} Q_i. \tag{21}$$

D_i is the single-hop delay of Node i in multi-hop networks, from (20) and (21), D_i can be obtained as

$$\begin{aligned} D_i &= D_i^{que} + D_i^{mac} \\ &= \frac{payload}{offeredload} \frac{2Q_i - Q_i^2 + Q_i^3}{2(1 - Q_i)}. \end{aligned} \tag{22}$$

From (22), the end-to-end delay D can be obtained as

$$\begin{aligned} D &= \sum_{i=0}^{H-1} D_i \\ &= \frac{payload}{offeredload} \sum_{i=0}^{H-1} \frac{2Q_i - Q_i^2 + Q_i^3}{2(1 - Q_i)}. \end{aligned} \tag{23}$$

Using the expression of (7), the value of end-to-end delay can be obtained.

Table 1: System parameters

Packer payload(DATA)	200 bytes
PLCP Preamble	16 μsec
PLCP header(single)	4 μsec
MAC header	24 bytes
LLC header	8 bytes
ACK size	10 bytes
Data rate	18 Mbps
ACK bit rate	12 Mbps
Transmission range	60m
Carrier sensing range	115m
Distance of each node	45m
$FRAME$	128 μsec
$DATA$	92 μsec
ACK	32 μsec
SIFS time	16 μsec
DIFS time	34 μsec
slot time	9 μsec
CW_{Min}	31
CW_{Max}	1023
Retransmission	7

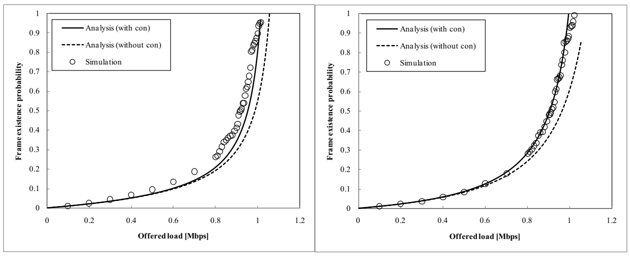

Figure 3: Frame existence probabilities of node 0 and node 2 in 7 hop network as a function of offered load

3. Simulation Verification

This section shows the analytical predictions and ns-2 simulation results for the multi-hop network as shown in Fig. 1. Table 1 gives system parameters used in analytical derivations and simulations. In ns-2 simulations, The UDP frames are generated at Node 0, which are relayed to Node H.

Figure 3 shows the frame existence probabilities of node 0 and node 2 in 7-hop network as a function of offered load. In 7-hop network, simulation result shows node 2 is the bottle-neck node [1]. However, There are differences appear between the analytical predictions without concurrent-transmission collisions and simulation result. When offered load is near maximum throughput point, collisions of concurrent-transmission increase so much that the collisions can not be ignored. Therefore, it is seen from Fig. 3 that the analytical predictions which consider the concurrent-transmission collisions agree with the simulation results better, which shows validity of the analysis.

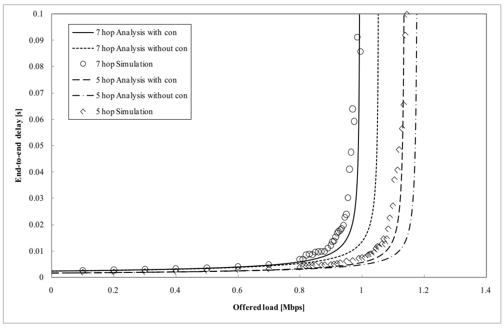

Figure 4: End-to-end delay of 5, 7 hop networks as a function of offered load

Figure 4 shows the end-to-end delay of 5, 7 hop networks as a function of offered load. It is seen from Fig. 4 that the analytical predictions agree with the simulation results qualitatively, which shows validity of the analysis.

4. Conclusion

This paper has presented analytical expressions for the end-to-end delay at IEEE802.11 multi-hop networks with string topology, the hidden-node collisions and concurrent-transmission collisions are considered. The validities of the analytical expressions are confirmed from the agreements between the analytical and simulation results.

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