Per-Flow Fair Media Access Control in Wireless Ad-Hoc Networks

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SUMMARY IEEE 802.11 Media Access Control (MAC) is the most widely used protocol in Wireless Ad-hoc Networks (WANETs). However, it cannot guarantee fair channel allocation among the flows contending for the channel. In this paper, we propose a new media access control algorithm to achieve per-flow fairness while maximizing WANETs throughput.

key words: IEEE 802.11 MAC, per-flow fairness, ad-hoc

1. Introduction

IEEE 802.11 [1] is the most widely used protocol in the WANETs. The basic media access control mechanism of IEEE 802.11 is the Distributed Coordination Function (DCF) with Carrier Sensing Multiple Access/Collision Avoidance (CSMA/CA). The DCF includes a backoff algorithm called Binary Exponential Backoff (BEB). The BEB prefers the last successful node because the Contention Window (CW) size of the last successful node is always smaller than those of the unsuccessful nodes. This preference yields unfair channel allocation among the nodes [2]–[4]. Hence, there have been many studies to solve this problem [5]–[7]. However, if all the nodes share the channel fairly, the per-flow throughput of the node transmitting the large number of the flows is lower than that of the node transmitting the small number of the flows. To achieve the per-flow fairness, the authors of [8] introduce a distinct backoff mechanism to all the flows in a node. However, they classify the flows by the service priority not by the source-destination pair. Thus, the algorithm of [8] cannot guarantee to allocate more channel capacity to the nodes having a number of flows. On the other hand, the algorithms of [9]–[11] consider the fairness with the number of flows of a node. However, they cannot guarantee to achieve the maximum throughput and the per-flow fairness simultaneously.

In this letter, we propose the Per-flow Fair MAC (PFMAC) to guarantee the per-flow fairness and the maximum network throughput in the single-hop WANETs. In addition, we verify the performance of the PFMAC through the stability analysis and simulations.

2. Per-Flow Fair MAC (PFMAC)

We assume that all the nodes can hear the transmissions of the other nodes and the number of the transmitting flows of each node does not change. In the PFMAC, node $i$ randomly selects the backoff time over the interval $[0, CW_i]$ with a uniform distribution, where $CW_i$ is the contention time size for node $i$. Thus, the average backoff time of node $i$ is represented as $\frac{CW_i}{2}$, $1 \leq i \leq m$, and $m$ is the number of the nodes contending for the channel. Since the backoff timer of a node is frozen when the other node sends a packet, we assume that the time scale for the backoff mechanism excludes the frozen time. Then, it seems that a packet transmission occupies one slot in Fig. 1 [12]. Assume that the duration of $[n, n+1]$ is composed of $T$ slots which is the predefined update interval of the PFMAC on the reduced time scale. Let $y_i(n)$ be the expected number of packets that node $i$ transmits during $[n, n+1]$. Then, we show that $y_i(n) = r_i(n)T$ where $r_i(n)$ is the packet transmission probability of node $i$ at a given slot during $[n, n+1]$ and described as follows:

$$r_i(n) = \frac{2}{CW_i(n)^a}, \quad 1 \leq i \leq m$$

(1)

Therefore, if node $i$ can determine the proper $y_i(n)$, then $CW_i(n)$ is obtained from (1).

Let $P_i(n)$ be the $n$-th estimated channel collision probability of node $i$. Then, in the PFMAC, node $i$ updates $y_i(n)$ every $T$ slots as follows:

$$y_i(n+1) = y_i(n) + \alpha[F_i(1 - P_i(n)) - P_i(n)y_i(n) + F_iP_i(n)]$$

$$q_i(n+1) = q_i(n) + (P_i - P_i(n))$$

(2)

\[\text{backoff timer is frozen}\]

\[\text{: original time scale}\]

\[\text{: reduced time scale}\]

\[\text{: transmission starting slot}\]

\[\text{: transmission ongoing slot}\]

\[\text{: empty slot}\]

\[\text{Fig. 1 Reduced time scale.}\]
where \( \alpha \) is the control gain, \( F_i \) is the number of outgoing flows of node \( i \), and \( P_o \) is the optimal channel collision probability when the maximum network throughput is achieved. As it follows from (2), the PFMAC is designed to assign more channel resource to the nodes originating more flows and also designed to give the penalty to the nodes inducing more network traffic. In addition, \( q_i(n) \), the accumulated difference between \( P_o \) and \( P_i(n) \), is introduced to achieve the maximum network throughput. We show how \( P_o \) is estimated in Sect. 4.

3. Throughput Analysis of PFMAC

For the convenience, we only consider the static networks. Thus, \( m \) is fixed and there is no mobility of nodes. In order to compare the maximum throughput of the PFMAC with that of the original DCF, we use the same analysis technique as shown in [13]. Therefore, we assume that the number of the nodes is fixed and only focus on the saturation condition, i.e., every node always has a packet to be transmitted. The channel error is not taken into account. However, we do not assume that all the nodes have the identical contention window size at the steady state because the PFMAC is designed to assign the different contention window size to each node depending on its number of flows.

Let \( P_{tr} \) be the probability that there is at least one transmission in the steady state. Then, it is expressed as follows:

\[
P_{tr} = 1 - (1 - r_1^*) \cdots (1 - r_m^*)
\]

where \( r_i^* \) is the steady state transmission probability of node \( i \). Then, the probability, \( P_s \), that a successful transmission occurs is

\[
P_s = [r_1^*(1 - r_2^*) \cdots (1 - r_m^*) + \cdots + r_m^*(1 - r_1^*) \cdots (1 - r_{m-1}^*)]/P_{tr}
\]

(4)

Let \( E[\Theta] \) be the average channel free time between the consecutive packet transmissions. Then, it is easy to show \( E[\Theta] = \sigma(\frac{1}{P_{tr}} - 1) \) where \( \sigma \) is the duration of a time slot. Denoting \( E[PKT] \) as the average packet payload size, the saturation throughput \( S \) is shown as follows [13]:

\[
S = \frac{P_o E[PKT]}{\sigma E[\Theta] + P_o T_s + (1 - P_o)T_c}
\]

(5)

where \( D = \frac{P_o E[PKT]}{\sigma E[\Theta] + P_o T_s + (1 - P_o)T_c} \), \( T_s \) is the duration of a successful transmission, and \( T_c \) is the duration of a collision. \( T_s \) and \( T_c \) are measured in slot time unit. As it follows from (5), since \( E[PKT] \), \( \sigma \), \( T_s \), and \( T_c \) are constants, \( D \) has to be maximal for the maximum \( S \). Since the minimum \( CW/n \) is usually much larger than 2, we know that \( r_i(n) \) is always much smaller than 1 from (1) and hence, \( r_i^* \ll 1 \) and \( D \) can be approximated as follows:

\[
D \approx \frac{r_1^*(1 + r_1^* - R^*) + \cdots + r_m^*(1 + r_m^* - R^*)}{T_c - (T_c - 1)(1 - R^*)}
\]

(6)

where \( R^* = \sum_{i=1}^{m} r_i^* \). Differentiating \( D \) with \( R^* \), we obtain the optimal \( R_o \) which guarantees the maximum saturation throughput, i.e.,

\[
R_o = \frac{-1 + \sqrt{\frac{1}{T_c}}}{T_c - 1}
\]

(7)

If we use \( T_s^{rtr} \) and \( T_c^{rtr} \) of [13] and set \( E[PKT] \) to 8184 bits, then the maximum saturation throughput normalized with 1 Mbps channel capacity is 0.82, which is very close to that of the original IEEE 802.11 DCF [13].

4. Estimation of Optimal Channel Collision Probability

Since we assume that \( r_i(n) \ll 1 \) for all \( i \), \( P_i(n) \) is approximated as follows:

\[
P_i(n + 1) = 1 - (1 - r_i(n)) \cdots (1 - r_m(n))
\]

\[
\approx r_i(n) + \cdots + r_m(n)
\]

\[
\vdots
\]

\[
P_m(n + 1) \approx r_1(n) + \cdots + r_{m-1}(n)
\]

(8)

If there are sufficiently many nodes contending for the channel, we can approximate that \( P_i(n) \approx P(n) \) for all \( i \) because the traffic from one node is negligibly small compared to the whole network load. Therefore, from (8), we obtain

\[
\sum_{i=1}^{m} P_i(n + 1) = mP(n + 1) = (m - 1)R(n)
\]

where \( R(n) = \sum_{i=1}^{m} r_i(n) \). Hence, we show

\[
P(n + 1) = \frac{m - 1}{m}R(n) = \frac{m - 1}{m}Y(n)
\]

(9)

where \( Y(n) = \sum_{i=1}^{m} y_i(n) \). From (9), we obtain \( P_o = \frac{m - 1}{m}R_o \).

5. Fairness and Stability Analysis of PFMAC

We set the initial value of all \( q_i(n) \) to be identical. Then, we can approximate \( q_i(n) \approx q(n) \) because \( P_i(n) \approx P(n) \) as shown in Sect. 4. Then, from (2) and (9), we obtain

\[
y_i(n + 1) = y_i(n) + \alpha[F_i(1 - P(n)) - P(n)y_i(n) + F_i q(n)]
\]

(10)

\[
q(n + 1) = q(n) + (P_o - P(n))
\]

\[
P(n + 1) = \frac{m - 1}{m}Y(n)
\]

From (10), the steady state is

\[
y_i^* = \frac{F_i[(1 - P^*) + q^*]}{P^*}
\]
where \( Y' = \frac{mT}{m+1} P_o \). As it follows from (11), since \( \frac{Y'}{P'} \) is independent of \( i \), it is shown that the PFMAC achieves the per-flow fairness.

Let us define \( X(n) = [Y(n) q(n) P(n)]^T \). After linearization at the equilibrium point, (10) is written as follows:

\[
X(n+1) = AX(n)
\]

(12)

where

\[
A = \begin{bmatrix}
1-aP_o & a \sum_{i=1}^{m} F_i - a \left( \frac{mTP_o}{m+1} + \sum_{i=1}^{m} F_i \right) \\
0 & 1 \\
\frac{m-1}{m} & 0 & 0
\end{bmatrix}
\]

and the characteristic equation of \( A \) is

\[
\Phi(z) = z^2 + (\alpha P_o - 2)z^2 + (1 + \alpha k)z - \alpha P_o
\]

where \( k = \frac{MF}{T}, M = \frac{m-1}{m}, \) and \( F = \sum_{i=1}^{m} F_i \). From the Jury’s criterion, the overall system is stable if \( \alpha \) is chosen to satisfy

\[
0 < \alpha < \min \left\{ \frac{1}{P_o}, \frac{2P_o - P_o^2}{P_o^2} \right\}
\]

(13)

6. Simulations

In the simulations, \( m \) nodes are randomly deployed in 100 m by 100 m flat area. The transmission range of a node is 250 m. All packets are of the same size and not fragmented. There is no mobility of nodes. The nodes are classified into two sets, that is, the one is the set of the nodes with 1 flow, and the other is the set of the nodes with \( n \) flows. Each set includes \( m/2 \) nodes respectively. We assume that each node adopts the fair queueing algorithm such as round robin. The system parameters are listed in Table 1. The update interval \( T \) is set to 3000 slots and the simulation is run for 300 sec. Every sample points in the figures represent the average values from 100 simulation runs. The maximum and the minimum contention window size are \( CW_{\text{max}} = 1023 \) and \( CW_{\text{min}} = 31 \) respectively. In this simulation, we set \( \alpha = 0.2 \) which satisfies the stability condition in (13).

Figure 2 illustrates the expected number of packet transmissions at the individual node during \( T \) slots. The lines denoted by \( y_1 \) and \( y_2 \) are the results of the nodes which have 1 flow and \( n \) flows respectively. They are the calculated results from (10). On the contrary, \( y_3 \) and \( y_4 \) are the simulation results of the nodes which have 1 flow and \( n \) flows respectively. Figure 2 shows that the packet transmission probability is inversely proportional to \( m \). However, the node with \( n \) flows always transmits almost \( n \) times more packets than the node with 1 flow regardless of \( m \). In addition, it also shows that the simulation results are similar to those of the approximated model. Since each node estimates \( P(n) \) individually in the real networks, large \( \alpha \) may
cause the unfairness among the flows. If the copy and diffusion mechanism in [10] is applied, all the nodes are able to share the same $P(n)$, and hence, the per-flow fairness can be guaranteed even if $\alpha$ is large.

Figure 3 depicts the saturation throughput normalized with the channel capacity according to the number of nodes. As shown in Fig. 3, the PFMAC maintains the maximum throughput regardless of the number of the nodes while the throughput performance of IEEE 802.11 DCF is degraded as the number of nodes increases. This is because each node controls its packet transmission probability properly in the PFMAC.

In Fig. 4, we show the fairness index [14] calculated on each flow. As shown in Fig. 4, the PFMAC improves the per-flow fairness compared to the IEEE 802.11 DCF.

7. Conclusions

In this letter, we propose the PFMAC. The PFMAC improves the per-flow fairness of channel allocation with the maximum network throughput. Moreover, there is no additional exchange of the network information because the PFMAC operates only with the local information. We show the per-flow fairness and the stability of the networks through the analytical investigation and simulations.

References