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Achieving Weighted Fairness between Uplink and Downlink in IEEE 802.11 WLANs with an Enhanced DCF

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Abstract: -Fair allocation of bandwidth and maximization of channel utilization are two important issues when designing a contention-based wireless medium access control (MAC) protocol. It is particularly important in IEEE 802.11 wireless local area networks (WLANs) because the networks are known to have unfairness problem between uplink and downlink accesses. To solve this problem, we use an enhanced DCF to obtain the optimal transmission probabilities for access point (AP) and wireless stations (STAs) in the sense of weighted fairness and system throughput maximization. The efficiency of the protocol is evaluated with both analysis and simulation. The results show that with the protocol, we can achieve the design goals under different numbers of nodes and different weighted fairness between the accesses in the networks.

Key-Words: - Weighted Fairness, Throughput Maximization, IEEE 802.11 WLANs, MAC, DCF.

1 Introduction

IEEE 802.11 [1] has become one of the most important and successful MAC protocols for wireless infrastructure and infrastructureless (i.e., *ad hoc*) LANs. Given its popularity, IEEE 802.11 DCF, however, does not provide service differentiation, such as throughput and delay guarantees, among connections of different priorities. It also does not consider fair allocation of bandwidth that has also been identified as one of the most important issues when designing a contention-based wireless MAC protocols.

For these problems, many related works have been done to develop scheduling algorithms for the wireless network. However, most of them are centralized or polling-based protocols. More recently, with the distributed EDCF in IEEE 802.11e, some works have also been done for service differentiation by using different priority schemes based on, for example, setting different IFS, CW, or back-off parameters specified in the MAC. However, these previous works are usually conducted for either performance maximization or weighted fairness in the networks. Only few related works may take both design goals into account with a distributed mechanism.

In these few works, [2] attempts to deal with this problem in a multi-hop wireless network subject to a minimum fairness guarantee, which is different from the issues we address on the WLANs. [3] provides a so-called P-MAC that modifies the DCF to achieve the two goals, but it uses a constant contention window and requires modifications to the DCF. [4] extends the work in [5], and derives a value p for each class to maximize the system capacity while ensuring a user-specified utilization ratio. This work, however, is based on the so-called *p-DCF* proposal in IEEE 802.11e, which does not follow the binary exponential back-off procedure in the legacy DCF. In [6], we propose a p-persistent enhanced DCF protocol, namely *P-IEEE 802.11 DCF* that can obtain the maximum overall throughput in a WLAN. With the throughput being maximized, however, it does not consider the problem of unfair share between upstream and downstream accesses in the network.

In this work, we solve the fairness problem not considered in the above while maximizing the system throughput. To this end, we first model a WLAN with a general backoff distribution using a two-state Markov chain. With this model, we then explore the effects of directly manipulating a node's transmission probability as the service differentiation mechanism between the upstream and downstream traffic flows in a WLAN while maximizing the system throughput in the network. Specifically, we introduce a method to obtain the optimal probabilities for the weighted fairness, with the Markov model. To verify its correctness, we simulate a WLAN with different weights between AP and STAs and different number of nodes in the WLAN. And finally, the conclusion is drawn to comment the results and summarize our work.

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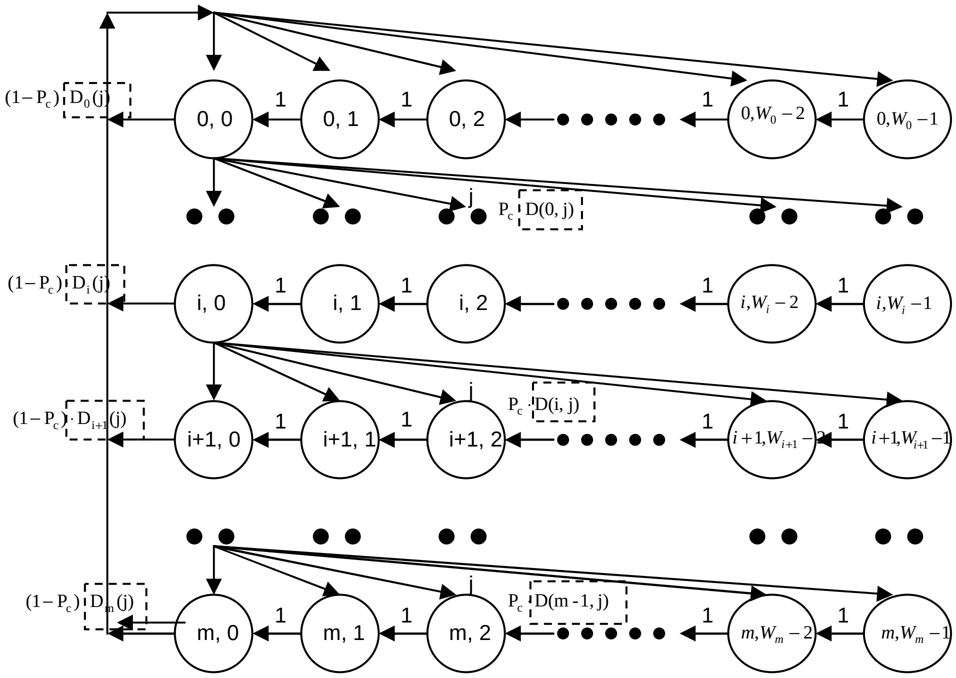


Fig. 1: Markov chain model with a general backoff distribution

2 Analytic Model

In this section, we give a discrete-time Markov chain model for WLAN, based on [7]. As shown in Fig.1, this model takes into account not only the binary backoff procedure, but also a general backoff distribution that is not considered in the previous work. In this figure, *i* and *j* denote the stochastic processes representing the back-off timer and the back-off stage, respectively, and construct a state (*i,j*) in the model. Specifically, when a frame transmission results in collision or success in state (*i,j*), the transmission probability from state (*i,0*) to (*i+1,j*) or to (*0,j*) is obtained according to the backoff distribution $D(i, j)$ or $D_i(j)$.

Moreover, it should satisfy the following constraint to be a reasonable distribution:

$$(1-P_c)\sum_{j=0}^{W_0-1} D_i(j) + P_c \sum_{j=0}^{W_i-1} D(i, j) = 1 \tag{1}$$

for all $i \in (0, \mathrm{m})$, where *m* denotes the maximum number of retransmission, and P_c denotes the collision probability of a node. With the constraint, in fact many distributions are possible for the backoff. However, DCF simply chooses a uniform distribution as

$$D_i(j) = \frac{1}{W_0}$$
$$D(i, j) = \frac{1}{W_i} \tag{2}$$

The choice may be suitable for light-weight traffic because in the situation a node rarely transmits its frames in spite of the distribution. But when the network is saturated, each node will try to transmit its frames whenever it reaches state $(i,0), i \in (0,m)$, which will lead to a high collision probability and thus low overall system throughput.

Apparently, to achieve the maximum system throughput, we should change the distribution properly when the network is saturated. This is done here by setting a filtering probability, namely P_e, to further constraint the transmission probability of a node, while adopting the same uniform distribution of IEEE 802.11 DCF when a node reaches its state (*i,0*). More precisely, we have the following distribution

$$D_i(j) = \frac{P_e}{W_0}$$
$$D(i, j) = \frac{1 - P_e \cdot (1-P_c)}{P_c \cdot W_i} \tag{3}$$

which also satisfies the constraint of (1). With the above, we preserve the simplicity of IEEE 802.11 DCF because it still uses a uniform distribution for the binary backoff procedure. In addition, with the

$$b_{0,0}=\frac{2(1-2\widetilde{P})(1-\widetilde{P})}{W_0\cdot(1-(2\widetilde{P})^{m'+1})\cdot(1-\widetilde{P})+(1-2\widetilde{P})(1-\widetilde{P}^{m+1})+W_0 2^{m'}\widetilde{P}^{m'+1}(1-2\widetilde{P})(1-\widetilde{P}^{m-m'})},\quad m>m' \quad (4)$$

aid of P_e, we can easily control the system to achieve the maximum throughput.

For this goal, we should analyze the network throughput with the above distribution as the first step. This is started by solving the Markov model in Fig. 1 with the distribution in (3). As shown in the Appendix, this can be done with some algebraic manipulations, which leads to the stationary probability of state (0,0) shown in (4) on the top of this page (where m' denotes the largest contention window size and $\widetilde{P}=1-(1-P_c)\cdot P_e$). Given that, the probability τ that a node transmits a frame in a random time slot can be obtained as

$$\tau=\sum_{i=0}^{m}P_e\cdot b_{i,0}=P_e\cdot\frac{1-\widetilde{P}^{m+1}}{1-\widetilde{P}}\cdot b_{0,0} \quad (5)$$

where $b_{i,0}$ denotes the stationary probability of (i,0). With the above, we now come to the step of obtaining the optimal transmission probabilities for AP and STAs. Its calculations are shown in the following section.

3 Weighted Fairness between Upstream and Downstream Traffic

In this section, we provide a method to solve the weighted fairness problem under consideration. At first, the flows from AP to STAs are defined to be the downstream traffic and those from STAs to AP to be the upstream traffic. Furthermore, let $P_{s,AP}$ be the probability that a MAC frame is transmitted from AP and success, and $P_{s,STA}$ be the probability for STAs. Similarly, let ψ_{AP} and ψ_{STA} denote the fairness weights for AP and STAs, respectively. With these, it is considered that the traffic flows within a WLAN would fairly share the wireless medium and the weighted fairness in the WLAN is achieved, in a probabilistic sense, if the following condition holds,

$$\frac{P_{s,AP}}{\psi_{AP}}=\frac{P_{s,STA}}{\psi_{STA}} \quad (6)$$

Since the two probabilities involved can be obtained as $P_{s,AP}=\tau_{AP}\cdot(1-\tau_{STA})^{N_{STA}}$ and $P_{s,STA}=\tau_{STA}\cdot(1-\tau_{STA})^{N_{STA}-1}\cdot(1-\tau_{AP})$ (where N_{STA} denotes the number of wireless stations in the WLAN), then the equation (6) can be rewritten as

$$\tau_{AP}=\frac{\psi_{AP}\cdot\tau_{STA}}{\psi_{STA}-\psi_{STA}\cdot\tau_{STA}+\psi_{AP}\cdot\tau_{STA}} \quad (7)$$

Given the above, we can find the optimal transmission probability of AP, namely $\tau_{AP,opt}$, that can achieve the maximum system throughput if the optimal transmission probability of STAs, namely $\tau_{STA,opt}$, in the same sense can be obtained. For this, the throughput calculation should be given at first

$$\begin{aligned} S&=\frac{P_s\cdot E[P]}{(1-P_{tr})\cdot\sigma+P_s\cdot T_s+(P_{tr}-P_s)\cdot T_c}\\ &\times\frac{1}{P_s}\\ &=\frac{E[P]}{T_s-T_c+\dfrac{P_{tr}\cdot T_c+(1-P_{tr})\cdot\sigma}{P_s}}\end{aligned} \quad (8)$$

where P_s and P_{tr} denote the probability that a successful transmission occurs in a slot time, and the probability of at least one transmission in a slot time, respectively. σ, T_c, and T_s represent the duration of an empty slot time, and the average time that the channel is sensed busy due to a successful transmission or a collision, respectively.

From the throughput calculation, we can see that if the denominator part can be minimized, the throughput S can be maximized. Thus, we define the following for optimization

$$S^f=\frac{P_s}{P_{tr}\cdot T_c+(1-P_{tr})\cdot\sigma} \quad (9)$$

With the above, it can be shown that S^f depends on τ_{STA}. Thus we can solve the equation

$$\frac{dS^f}{d\tau_{STA}}=0 \quad (10)$$

to obtain the optimal probability $\tau_{STA,opt}$ that can maximize the aggregate system throughput. Letting $T_c^*=T_c/\sigma$ and performing some other algebraic manipulations, the optimal can be obtained as

$$\tau_{STA,opt}=\frac{\sqrt{(6\cdot T_c^*-1)\cdot N_{STA}^2+(T_c^*-1)^2}-(T_c^*+N_{STA}+1)}{T_c^*\cdot(3\cdot N_{STA}^2-N_{STA}-2)-N_{STA}\cdot(N_{STA}+1)} \quad (11)$$

Finally, taking the above into (7), we can find $\tau_{AP,opt}$.

Now, with the optimal transmission probabilities ($\tau_{AP,opt}$ and $\tau_{STA,opt}$) and the number of wireless stations (N_{STA}), we can solve the nonlinear system of equations of (5) to find the filtering probability for AP ($P_{e,AP}$) and that for STAs ($P_{e,STA}$). Then, with these probabilities, we can obtain the backoff distribution that can satisfy the desired fair share between the upstream and downstream traffic, and can maximize the system throughput at the same time. At the end, we perform several simulation studies to verify its effectiveness, as shown in the next section.

4 Performance Evaluation

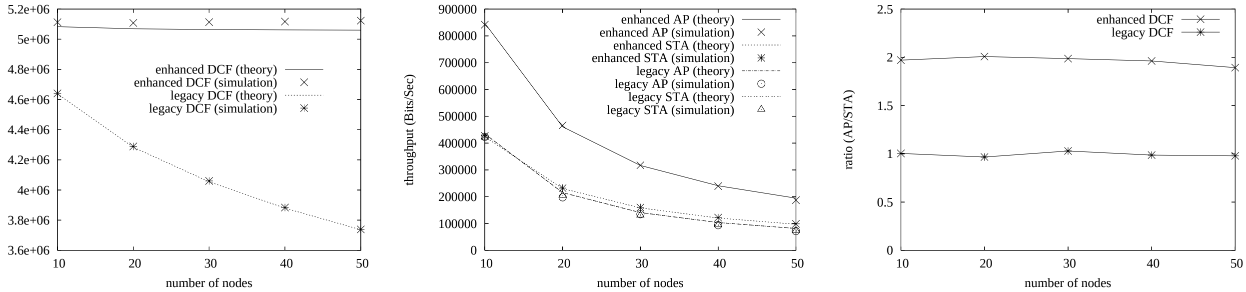
In this section, we report on experiments made in order to verify the theoretical results derived previously. Specifically, we want to show that the enhanced DCF is able to achieve the weighted fairness between upstream and downstream traffic and is able to maximize the system throughput in a WLAN.

To this end, we implement the enhanced DCF with a simulator, in which all STAs are assumed to have an IEEE 802.11a interface and to be uniformly distributed in the WLAN. Each STA has a seamless flow with 2000-bytes of UDP packets toward AP while AP has the same flow toward a randomly chosen STA, resulting in the saturated traffic as required. In addition, to focus on the throughput analysis, we adopt the same assumption of [7] that no hidden terminal problem exists in the WLAN. With the above, we conduct a sequence of simulations to verify the enhanced DCF with different data rates in the 802.11a PHY and different fairness weights between the upstream and downstream traffic. However, due to space limitations, we show only the results of 6 Mbps data rate in the PHY and two different weights between the traffic. Moreover, for the sake of comparison, we also simulate the legacy DCF with the same setting in the WLAN.

The simulation results are shown in Figs. 2 and 3. In both figures, the performance metrics under consideration are aggregate system throughput (as shown in (a)), average throughput of a node (as shown in (b)), and throughput ratio (as shown in (c)). The last metric is obtained by the throughput of AP divided by that of a station, which represents the weighted fairness of $\psi_{\mathrm{AP}} / \psi_{STA}$. The number of nodes that excludes AP is ranged from 10 to 50, which represents the normal usage of a WLAN. In addition, the theory and simulation results of the first two metrics are shown with lines and symbols, respectively, in (a) and (b) of both figures while the simulation results for the last metric (throughput ratio) are shown in (c) with lines and also symbols.

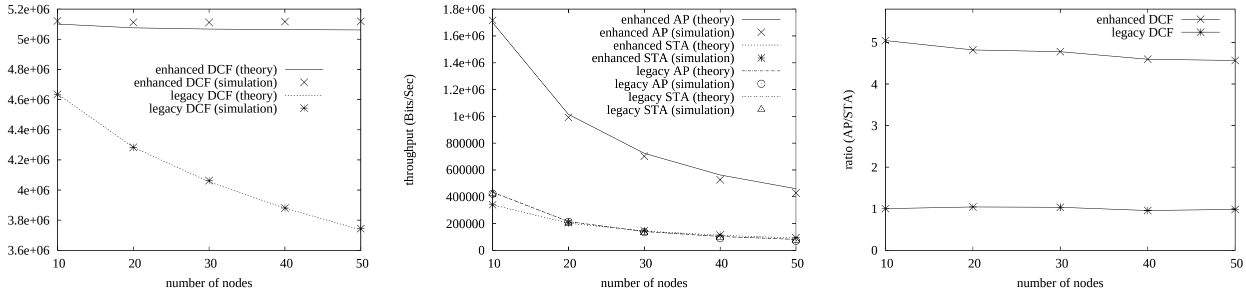
As shown in the figures, the results confirm the efficiency of the enhanced DCF. It is shown in (a) that the aggregate system throughput of the enhanced DCF has almost the same maximum value in spite of the number of nodes. It implies that even with different fairness weights ($\psi_{\mathrm{AP}} / \psi_{STA}$ = 2 and 5), the best P_e s can still be obtained to achieve the maximum throughput in spite of the competition level (i.e., the number of nodes). This is because we can more aggressively suppress the transmission possibility of a node by using a lower P_e when the number of nodes increases. Thus, by choosing an optimal value of P_e for a competition level, we can keep the system away from excess medium access contention while allowing reasonable access opportunity for each node to cooperatively achieve the maximum system throughput. On the other hand, without further constraint, the legacy DCF results in excess contention and low system throughput as the number of nodes increases, which is shown by the decreased curves in (a) of both figures.

The results for the weighted fairness are shown in (b) and (c) of both figures. In (b), we show the per-node throughput for AP and STA, respectively. From that, the throughput ratio between them can be also observed implicitly. However, to show the ratio more clearly, the ratio values are explicitly drawn in (b) as the number of nodes increases. With that, we can clearly see the fact that with the enhanced DCF, AP's throughput remains almost 2 or 5 times of STA's throughput in the two scenarios, respectively, despite the number of nodes. On the other hand, no difference on the throughput between AP and STAs can be obtained when the legacy DCF is adopted. This is the problem exists in WLANs that a legacy DCF can not achieve weighted fair share among the nodes in the environment. This happens because even though AP is the communication center of a WLAN, it still has the same transmission opportunity when compared with the STAs associated with it. Thus, the key concept for solving this problem is to let AP have more transmission probability for accommodating the heavy traffic to and from itself. Our enhanced DCF realizes this concept by changing the backoff distribution with an additional filtering probability, P_e . This is done directly by each node without possible complex calculation for the setting different IFS, CW, or back-off parameters in the legacy DCF. In addition, by means of the direct manipulation of transmission probability, we eliminate the possible errors resulted from the methods with the parameter changes that may achieve the optimal transmission probability only indirectly or approximately.



(a) (b) (c)

Fig. 2. Throughput results of the enhanced DCF and the legacy DCF with the ratio of $\psi_{AP} / \psi_{STA} = 2$: (a) aggregate system throughput, (b) average throughput of a node, and (c) throughput ratio.



(a) (b) (c)

Fig. 3. Throughput results of the enhanced DCF and the legacy DCF with the ratio of $\psi_{AP} / \psi_{STA} = 5$: (a) aggregate system throughput, (b) average throughput of a node, and (c) throughput ratio.

5 Conclusion

In this paper, we proposed and evaluated an enhanced DCF to achieve the weighted fairness between upstream and downstream traffic in WLANs. Experiment results indicate that the enhanced protocol can actually achieve the design goal and also maximize the system throughput, which is a hard task for the IEEE 802.11 MAC even not impossible.

When compared with other complex or incompatible modifications to the IEEE 802.11 MAC, this protocol has the characteristics of simplicity and complete distribution, and requires no extra message to be shared among cooperating neighbor nodes.

With direct manipulation of the transmission probability derived from a general backoff distribution, the protocol gets rid of the possible cumbersome adjustments for the existing parameters in the MAC. As a result, the protocol is considered as a more convenient alternate that can properly provide weighted fairness in WLANs, with a simple tunable filtering probability to be a new parameter that could be added in the 802.11e extensions, while remaining in compliance with the legacy DCF.

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Appendix

In this appendix, we show that the enhanced protocol with the distribution shown in equation (3) can be modeled with a two-dimensional discrete-time Markov chain $\{b(t), s(t)\}$. As shown in Fig. 1, $b(t)$ and $s(t)$ denote the stochastic processes representing the back-off timer and the back-off stage, respectively, for a given node at slot time *t*, and the non-null probabilities involved can be represented by

$$\begin{cases} P\{i,k \mid i,k+1\} = 1, & k \in (0, W_i - 2), \quad i \in (0,m) \\ P\{0,k \mid i,0\} = \dfrac{(1-P_c)\cdot P_e}{W_0}, & k \in (0, W_0 - 1), \quad i \in (0,m) \\ P\{i,k \mid i-1,0\} = \dfrac{1-(1-P_c)\cdot P_e}{W_i}, & k \in (0, W_i - 1), \quad i \in (1,m) \\ P\{0,k \mid m,0\} = \dfrac{1}{W_0}, & k \in (0, W_m - 1) \end{cases} \tag{12}$$

In particular, we let

$$\tilde{P} = 1 - (1 - P_c)\cdot P_e \tag{13}$$

and thus, $1 - \tilde{P} = (1 - P_c)\cdot P_e$. The designed probability, $\tilde{P}$, in fact relates the backoff process of contention window with the impacts resulted from the filtering probability, P_e, by replacing the conditional collision probability *P* in [7], which does not take such impacts into account, with the probability $\tilde{P}$ of Eq. (13). Given that and denoting the stationary distribution of the Markov chain with $b_{i,k}$, we have the following relationship between back-off stages:

$$\begin{aligned} & b_{i-1,0}\cdot \tilde{P} = b_{i,0} \\ & \rightarrow b_{i,0} = \prod\nolimits_{j=1}^{i} \tilde{P}\cdot b_{0,0} = \tilde{P}^{i}\cdot b_{0,0}, i \in (1,m) \end{aligned} \tag{14}$$

In addition, the relationship between the neighboring back-off states can be represented by

$$\begin{aligned} & b_{0,k} = b_{0,k+1} + \frac{1}{W_0}\cdot \\ & \left[(1-\tilde{P})\cdot \sum_{i=0}^{m-1} b_{i,0} + b_{m,0} \right], \quad k \in (0, W_0 - 1) \end{aligned} \tag{15}$$

and

$$b_{i,k} = b_{i,k+1} + \tilde{P}\cdot b_{i-1,0}, \; i \in (1,m), \quad k \in (0, W_i - 1) \tag{16}$$

From (14), (15) and (16), we can deduce for all $k \in (0, W_i - 1)$

$$\begin{aligned} b_{0,k} &= b_{0,k+1} + \frac{1}{W_0}\left[(1-\tilde{P})\cdot \sum_{i=0}^{m-1} b_{i,0} + b_{m,0} \right] \\ &= \frac{W_0 - k}{W_0}\cdot \left[(1-\tilde{P})\cdot \sum_{i=0}^{m-1} b_{i,0} + b_{m,0} \right] \end{aligned} \tag{17}$$

and for all $i \in (1,m)$ and $k \in (0, W_i - 1)$

$$b_{i,k} = \frac{W_i - k}{W_i}\cdot \tilde{P}\cdot b_{i-1,0} \tag{18}$$

With (14) and transition in the chain, equations (17) and (18) can be simplified as

$$b_{i,k} = \frac{W_i - k}{W_i}\cdot b_{i,0}, \quad 0 \le i \le m \tag{19}$$

Therefore, by using the normalization condition on the Markov process, we have

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} = \sum_{i=0}^{m} b_{i,0} \sum_{k=1}^{W_i - 1} \frac{W_i - k}{W_i} = \sum_{i=0}^{m} b_{i,0}\, \frac{W_i + 1}{2} \tag{20}$$

Taking (19) into (20), a solution for $b_{0,0}$ in terms of $\tilde{P}$ can be obtained by (4). Finally, since a node transmits a frame when the back-off timer reaches zero and the transmission probability P_e allows the transmission, the probability τ that a node transmits a frame in a random time slot is obtained by (5). Given that, the conditional collision probability P_c is considered in a time slot, at least one of the $n-1$ remaining nodes transmit. That is,

$$P_c = 1 - (1-\tau)^{N-1} \tag{21}$$

Consequently, equations (5) and (21) represent a nonlinear system, and can be solved by using numerical methods.

With the above, we can consider the throughput obtainable in the protocol. To this end, P_{tr} and P_s can be represented in terms of τ as

$$P_{tr} = 1 - (1-\tau)^{N}$$

and

$$P_s = \frac{N\cdot \tau \cdot (1-\tau)^{N-1}}{P_{tr}} \tag{23}$$

With these probabilities, we can express the normalized system throughput *S* as the ratio given in (8). Specifically, we consider the times involved in the above only for basic mode. That is,

$$\begin{cases} T_s &= DIFS + H + E[P] + \delta + SIFS + ACK + \delta \\ T_c &= DIFS + H + E[P^*] + SIFS + ACK \end{cases} \tag{24}$$

where *H* denotes the physical header plus the MAC header, and δ denotes the propagation delay. $E[P^*]$ represents the average length of the longest frame payload involved in a collision. With the consideration of the same frame size, $E[P^*]$ is now equal to $E[P]$.