Markov Chain Performance Model for IEEE 802.11 Devices with Energy Harvesting Source

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***Abstract*—The developments in technology have improved the efficiency of devices in storing energy from the environment and convert it into energy. Therefore, research in energy harvesting networks has aroused increasing interest to utilize harvested energy for data transmission. Nevertheless, previous studies do not devote much attention to utilize energy harvesting in the IEEE 802.11 protocol, whose medium access control (MAC) mechanism applies exponential random backoff without considering the time for recharge. In this paper, we propose a modified DCF integrating the IEEE 802.11 MAC and a device recharging model. A three-dimensional Markov chain is then constructed to evaluate the network performance, such as throughput and delay, of the modified DCF. This work contributes to further study on MAC protocol for energy harvesting networks.**

***Index Terms*—Energy Harvesting, IEEE 802.11, Markov Chain**

I. Introduction

Energy harvesting devices are devices equipped with energy harvesters that capture and accumulate power from environmental sources for communication usage. Unlike the traditional wireless sensors, energy harvesting devices function as a self-powered electronic system that supplies inexhaustible power to replenish themselves indefinitely. Such energy harvesting networks have increased research interests in a variety of applications, such as power management [1–4], relay issue [5], and the prediction of the harvested energy amount[6, 7].

The performance of IEEE 802.11 distributed coordination function (DCF) has been well studied. A Markov Chain based analysis framework of IEEE 802.11 DCF is first constructed by [8]. Based on [8], many enhanced works have been proposed, such as retry limit consideration [9], TCP performance [9], refinement for previous framework [8, 10], unsaturated conditions [11, 12], and imperfect channel [13]. The original design of IEEE 802.11 DCF, however, does not accommodate an energy harvesting network that handles energy replenishment. To deal with this problem, our MAC protocol integrates backoff randomization and power replenishment, improving the transmission efficiency for an energy harvesting network.

This paper is organized as follows. In section II, we describe the system models, including the energy harvesting model, discrete time scale model, and the modified IEEE 802.11 DCF model with energy harvesting. In section III, we apply Markov chain approach to evaluate the collision probability, saturation transmission throughput and delay. Section IV illustrates some numerical results of the system performance, and section V concludes this paper.

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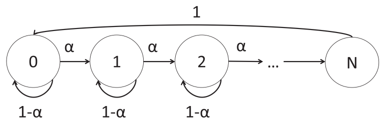

Fig. 1. Energy Model

II. System Model

A. Modification to the 802.11 DCF

Our main modifications are (1) To proceed a new transmission, the STA should have energy more than E_{Tx}, which is the maximum possible energy needed for a transmission. (2) After a transmission either success or failure, the STA should enter a recharging state until its energy exceeds E_{Tx}.

B. Energy Model

Several kinds of energy harvesting model have been proposed, such as constant rate model in [14, 15], Poisson process model in [1, 16], stationary/ergodic process model in [5, 17] [3], or Markov chain model in [2, 4, 6]. We choose the Poisson process in [5] as our energy model and transfer it into Bernoulli process to adapt a slotted CSMA/CA system. The energy states of a STA can thus be modeled as a discrete time Markov chain $e(t) \in \{0, 1, \cdots N-1\}$ as shown in Fig. 1, in which $e(t)$ denotes the amount of energy on a certain time slot, and α is the probability that the device is charged a certain amount of energy in the time slot. We assume an STA can transmit only when its energy exceeds the threshold energy E_{Tx}. Besides, we assume the energy to sensing channel status (busy or idle) is smaller than the recharging rate, so an STA can get positive net energy gain even if it keeps listening and recharging. Further, in our model an STA keeps listening in both backoff and energy recharging states. In every two consecutive states, the energy is differed by e_0 with a transition probability $\alpha = P\{e(t+1) = j+1 \mid e(t) = j\}$. We call α the charging probability. When $e(t) = N-1$, the STA has enough energy to transmit, and after a packet transmission its energy state is returned to $e(t+1) = 0$. The parameter N/α represents the average number of time slots for a full recharge, and it is given by $\frac{E_{Tx}}{e_0}$.

C. Model Time Scale

We define a discrete time scale in the system, in which a transition occurs whenever a STA in the system decreases its backoff counter. Thus, a model slot time can be an idle slot

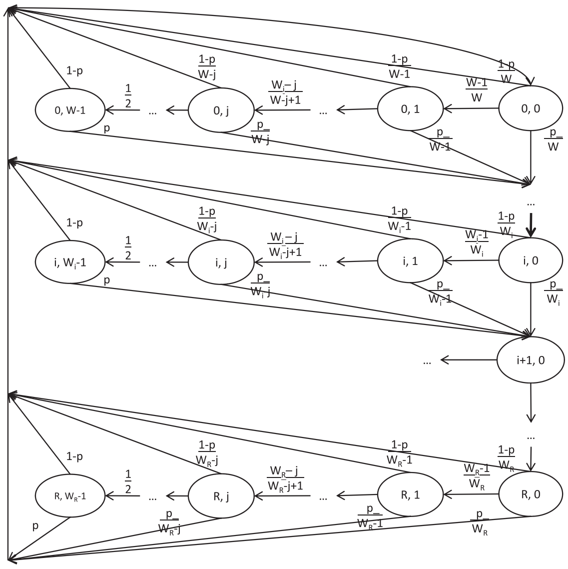

Fig. 2. Modified Bidimensional Markov Chain Model

time, a time interval including a successful transmission with an extra backoff slot, or a time interval including a collided transmission followed by an EIFS and an extra backoff slot. Note that in our modified DCF, the second case is different to the one in [18] since a consecutive transmission does not occur because the STA immediately enters the recharging state right after the transmission. When a STA enters the recharging state after a transmission, the remaining STAs in the channel will continue their backoff process regardless of the recharging STA. Nevertheless, the STA will keep performing carrier-sensing when in the recharging states and thus a synchronized backoff countdown among all contending STAs is remained.

D. Tridimensional Markov Chain

Our model is modified from [8], which models the contention process in IEEE 802.11 as a bidimensional Markov chain $\{s(t), b(t)\}$, and the state of each STA is described as $S_{i,j}$, where i is the backoff stage and j is the backoff counter at time slot t. Before introducing the third state variable, we made some transformation of the original bidimensional Markov Chain as shown in Fig. 2. Let W_i denote the contention window size at stage i and p be the conditional collision probability on the condition that a STA sends a packet. Since the backoff time is uniformly chosen from the range $[0, W_i - 1]$ after each transmission, and the backoff time counter is decreased by one at the end of each time slot, we let j be the modeled time slot elapsed in the current stage instead of the value of backoff counter. Therefore, for state $S_{i,j}$, a STA has probability $\frac{1}{W_i - j}$ to transmit, in which $\frac{p}{W_i-j}$ will collide and $\frac{1-p}{W_i-j}$ will succeed, and $\frac{W_i-j-1}{W_i-j}$ to make the backoff counter decrease by one and enter the next state $S_{i,j+1}$.

Our model can be expressed as a tri-dimensional Markov chain with state $S_{x,i,j}$, where x is respectively a, b, or c for recharging states after successful transmission, recharging states after collided transmission, and backoff states before transmission. Besides, i represents the i-th backoff stage, and j is the accumulated power level in this stage. For simplicity, we assume N is no less than the maximum contention window size, and a STA should always starts its backoff counting down after its accumulated energy level in the previous backoff stage reaches N.

A STA moves to those recharging states after each transmission. Thus, a STA in state $S_{c,i,j}$ would move to $S_{c,i,j+1}$ if the backoff counter is not zero, to $S_{a,i,j\prime}$ for successful transmission, and to $S_{b,i,j\prime}$ for collided transmission, where $j\prime$ is a binomial distribution with probability $\binom{j+1}{j\prime}\alpha^{j\prime}(1-\alpha)^{j+1-j\prime}$, meaning the accumulated power value of the j backoff slots in this stage.

III. System Analysis

A. Packet Transmission Probability

Let W be the minimum contention window size, we have the contention window size at backoff stage i to be

$$W_i = 2^i W \tag{1}$$

Then the nonnull one-step transition probabilities are

$$\begin{cases}
P\{c,i,j+1 \mid c,i,j\} = \frac{W_i-j+1}{W_i-j}, & j \in [0, W_i-2], i \in [0,R] \\
P\{a,i,j+1 \mid a,i,j\} = \alpha, & j \in [0,N-2], i \in [0,R] \\
P\{b,i,j+1 \mid b,i,j\} = \alpha, & j \in [0,N-2], i \in [0,R] \\
P\{a,i,j \mid a,i,j\} = 1-\alpha, & j \in [0,N-1], i \in [0,R] \\
P\{b,i,j \mid b,i,j\} = 1-\alpha, & j \in [0,N-1], i \in [0,R] \\
P\{a,i,j\prime \mid c,i,j\} & j\prime \in [0,j+1], i \in [0,R] \\
= \frac{(1-p)\binom{j+1}{j\prime}\alpha^{j\prime}(1-\alpha)^{j+1-j\prime}}{W_i-j}, & j \in [0, W_i-1] \\
P\{b,i,j\prime \mid c,i,j\} & j\prime \in [0,j+1], i \in [0,R] \\
= \frac{p\binom{j+1}{j\prime}\alpha^{j\prime}(1-\alpha)^{j+1-j\prime}}{W_i-j}, & j \in [0, W_i-1] \\
P\{c,i+1,0 | b,i,N-1\} = \alpha & i \in [0,R] \\
P\{c,0,0 | a,i,N-1\} = \alpha & i \in [0,R]
\end{cases} \tag{2}$$

The first equation in (2) considers that if the packet is not transmitted in the current time slot, then it is likely to be transmitted in the next time slot. The second and third equations considers that a STA is likely to be recharged to the next energy state with a probability α in the current time slot, and the forth and the fifth equation described that the STA remains in the same state if not recharged. The next two equations describe that, once a transmission occurred, the STA finds the corresponding recharging state depending on how much it had charged in the current backoff stage, where each recharging process is modeled as a Bernoulli process. The last two equations consider that when the STA is charged to the threshold, it is allowed to enter the next backoff stage.

Let $b_{x,i,j} = \lim_{t\to\infty} P\{x(t) = x, s(t) = i, b(t) = j\}, i \in \{0, R\}$ be the stationary probability. By inspection, we have

$$b_{c,i,j} = \frac{W_i - j}{W_i} b_{c,i,0} \tag{3}$$

and

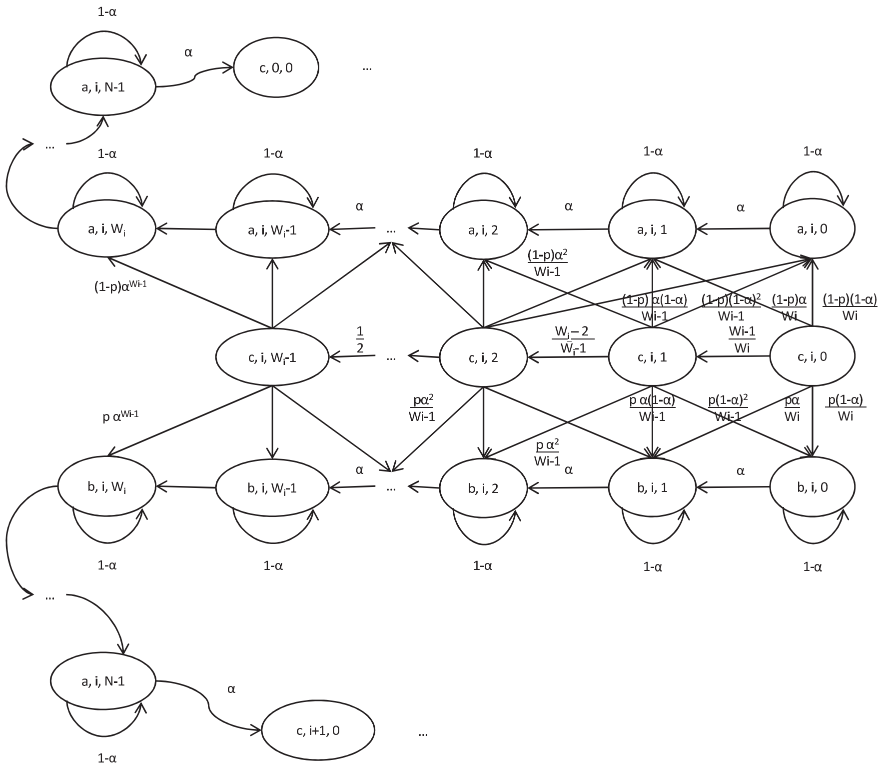

Fig. 3. Tridimensional Markov Chain Model in i-th backoff stage.

$$\begin{cases} b_{a,i,j} = \frac{1-p}{\alpha} b_{c,i,0}, & W_i \le j \le N-1 \\ b_{b,i,j} = \frac{p}{\alpha} b_{c,i,0}, & W_i \le j \le N-1 \end{cases} \quad (4)$$

$$b_{c,i,0} = \alpha \cdot b_{a,i-1,N-1} \quad (5)$$

Then, we solve for $b_{a,i,j}$ for $0 \le j \le W_i - 1$,

$$\begin{aligned} &b_{a,i,j} \\ &= \frac{b_{c,i,0}}{\alpha}\{\sum_{k=0}^{j-1}\frac{1-p}{W_i} + \sum_{k=j}^{W_i-1}\sum_{l=0}^{j}\binom{k+1}{l}\alpha^l(1-\alpha)^{k-l+1}\frac{1-p}{W_i}\} \\ &= \frac{1-p}{\alpha W_i}\{j + \sum_{k=j}^{W_i-1}\sum_{l=0}^{j}\binom{k+1}{l}\alpha^l(1-\alpha)^{k-l+1}\}b_{c,i,0} \quad (6) \end{aligned}$$

Similarly, $b_{b,i,j}$ for $0 \le j \le W_i - 1$ is

$$b_{b,i,j} = \frac{p}{\alpha W_i}\{j + \sum_{k=j}^{W_i-1}\sum_{l=0}^{j}\binom{k+1}{l}\alpha^l(1-\alpha)^{k-l+1}\}b_{c,i,0} \quad (7)$$

In order to impose the normalization condition, we first calculate

$$\sum b_{c,i,j} = \sum_{i=0}^{W_i-1}\frac{W_i - j}{W_i}b_{c,i,0} = \frac{1}{2}b_{c,i,0}(W_i+1) \quad (8)$$

and

$$\begin{aligned} &\sum_{j=0}^{W_i-1} b_{a,i,j} \\ &= \sum_{j=0}^{W_i-1}\{\frac{(1-p)b_{c,i,0}}{\alpha W_i}[j + \sum_{k=j}^{W_i-1}\sum_{l=0}^{j}\binom{k+1}{l}\alpha^l(1-\alpha)^{k-l+1}]\} \\ &= \frac{1-p}{\alpha}[\frac{W_i-1}{2} + (1-\alpha)\frac{W_i+1}{2}]b_{c,i,0} \quad (9) \end{aligned}$$

Then we get

$$\begin{aligned} &\sum b_{a,i,j} = \sum_{j=0}^{W_i-1} b_{a,i,j} + \sum_{j=W_i}^{N-1} b_{a,i,j} \\ &= \frac{1-p}{\alpha}[\frac{W_i-1}{2} + (1-\alpha)\frac{W_i+1}{2} + (N-W_i)]b_{c,i,0} \end{aligned} \quad (10)$$

Similarly,

$$\sum b_{b,i,j} = \frac{p}{\alpha}[\frac{W_i-1}{2} + (1-\alpha)\frac{W_i+1}{2} + (N-W_i)]b_{c,i,0} \quad (11)$$

With normalization condition,

$$\begin{aligned} 1 &= \sum b_{x,i,j} \\ &= \sum_{i=0}^{R}\{\sum_j b_{c,i,j} + \sum_j b_{a,i,j} + \sum_j b_{b,i,j}\} \\ &= \sum_{i=0}^{R}\{\frac{b_{c,i,0}\cdot N}{\alpha}\} = b_{c,0,0}\sum_{i=0}^{R}\{\frac{p^i N}{\alpha}\} \quad (12) \end{aligned}$$

from which

$$b_{c,0,0} = \frac{1-p}{1-p^{R+1}} \cdot \frac{\alpha}{N} \tag{13}$$

Now we calculate the probability τ that a STA transmits in a randomly chosen slot time. Let TX be the event a STA is found transmitting and $S = s$ be the event a STA is found in state s. Thus τ is given by

$$\begin{aligned}\tau = P\{TX\} &= \sum P\{TX|S=s\}P\{S=s\} \\ &= \sum_{i=0}^{R}\sum_{j=0}^{W_i-1} b_{c,i,j}\frac{1}{W_j - j} = \sum_{i}^{R} b_{c,i,0} = \frac{\alpha}{N}\end{aligned} \tag{14}$$

We can see that, the probability τ is dependent only on α, the charging probability, and N, the maximum energy capacity, which is different from [8]. This result is reasonable since each backoff stage has the same expectation length $\frac{N}{\alpha}$. Besides, since N is on the scale of thousands, τ is usually very small. Given n the number of contending STAs, from [8], we know that the conditional collision probability p is

$$p = 1 - (1-\tau)^{n-1}. \tag{15}$$

Observe that p is the function of α, N, and n rather than R since for either new packet transmission or retransmission, the average length of a backoff stage is always $\frac{N}{\alpha}$,

B. Throughput

Let P_b be the probability that the channel is busy and P_s be the probability that a successful transmission occurs in a modeled slot time. From [8], we already

$$P_b = 1 - (1-\tau)^n \tag{16}$$

$$P_s = n\tau(1-\tau)^{n-1} \tag{17}$$

We assume that in the system, each STA has a packet in the queue whenever it is charged to E_{Tx}. The normalized system throughput S, defined as the fraction of time the channel is used for successfully transmitting payloads, is

$$S = \frac{P_s E(P)}{(1-P_b)\delta + P_s T_s + [P_b - P_s]T_c} \tag{18}$$

Where $E(P)$ is the average packet payload size, T_s is the length of the modeled slot with a successful transmission, T_c is the length of the modeled slot with a collided transmission, and δ is the empty slot time. For the basic access mechanism,

$$T_s = T_{MPDU} + SIFS + T_{ACK} + DIFS + \delta \tag{19}$$

$$T_c = T_{MPDU} + SIFS + T_{ACK} + DIFS + \delta \tag{20}$$

In which T_{MPDU} is the time to transmit the MPDU (including MAC header, PHY header, and/or tail) and T_{ACK} is the ACK timeout. For the RTS/CTS case, T_s is given by

$$\begin{aligned}T_s = T_{RTS} &+ SIFS + T_{CTS} + SIFS \\ &+ T_{MPDU} + SIFS + T_{ACK} + DIFS + \delta\end{aligned} \tag{21}$$

$$T_c = T_{RTS} + SIFS + T_{ACK} + DIFS + \delta \tag{22}$$

In which T_{RTS} and T_{CTS} are the RTS/CTS timeout respectively. Since τ only relates to the energy harvesting parameters, the throughput S is independent to the contention windows size and the retry limit. Thus, to maximize the system throughput, we would like to adjust E_{Tx}, which is a function of τ. In order to find τ corresponding to the maximum throughput, we rearrange (18) into

$$S = \frac{E(P)}{\frac{1-P_b}{P_s}\delta + (\frac{P_b}{P_s}T_c) + T_s - T_c} \tag{23}$$

Taking the derivative of the denominator with respect to τ and then equating it to zero, we have

$$(T_c - \delta)(1-\tau)^n = T_c - (nT_c)\tau \tag{24}$$

Given τ, we can always find the STA number n to maximize the system throughput since $T_c - \delta > 0, n \geq 1, 0 \leq \tau \leq 1$. Further, when n is large ($n > 30$), (24) can be approximated as

$$(T_c - \delta)e^{n\tau} = T_c(1 - n\tau) \tag{25}$$

, which means the maximal system throughput can be reached when $n\tau = c$, where c is the solution of $(T_c - \delta)e^x = T_c(1-x)$. Substitute (24) and $c = n\tau$ into (18) and simplify, we have

$$S^* = \frac{E(P)}{\frac{(T_c-\delta)(1-\frac{c}{n})}{1-c} + T_s - T_c} \approx \frac{E(P)}{\frac{T_c-\delta}{1-c} + T_s - T_c} \tag{26}$$

Eq.(26) states that when n is large, different values of n also leads to approximately the same maximum throughput. Besides, since $n\tau$ is a constant and τ is small, the number of STA to reach the maximal throughput is much larger than that of original IEEE 802.11 DCF.

Given the optimized τ, we are able to measure the average energy gain e_0 in a modelled slot time $T_{slot} = (1-P_b)\delta + P_s T_s + [P_b - P_s]T_c$, in which P_b and P_s are functions of τ and n, and then find E_{Tx} by $E_{Tx} = \frac{N}{\alpha}e_0$.

C. Delay

The average access delay D is defined as the time elapsed between the moment the frame becomes HOL and the instant of time that the frame is successfully delivered. Follow the statement in [18] which applying Little's result, the delay with a finite retry limit is

$$D = \frac{n(1 - P\{LOSS\})}{S/E(P)} \tag{27}$$

where $P\{LOSS\}$ is the probability that the frame will be dropped in the end. With a similar approach as in [18], we first calculate the probability that the frame is found in the backoff stage i, according to (12), we have

$$\begin{aligned}P\{s=i\} &= \frac{1-p}{1-p^{R+1}}\frac{\alpha}{N}\frac{p^i N}{\alpha} \\ &= \frac{1-p}{1-p^{R+1}}p^i\end{aligned} \tag{28}$$

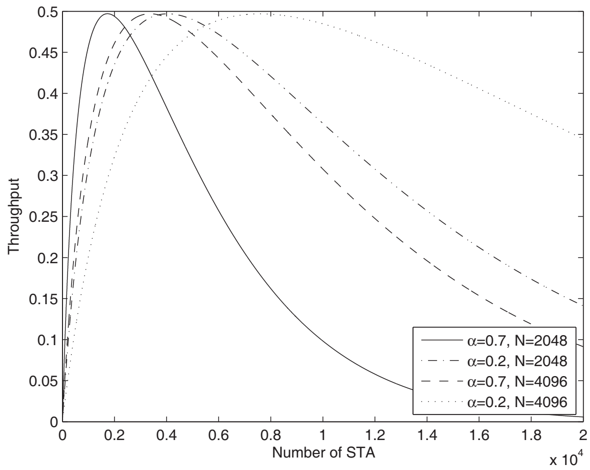

Fig. 4. Saturation throughput versus the number of contending STAs: $CW_{min} = 15$, $CW_{max} = 1023$

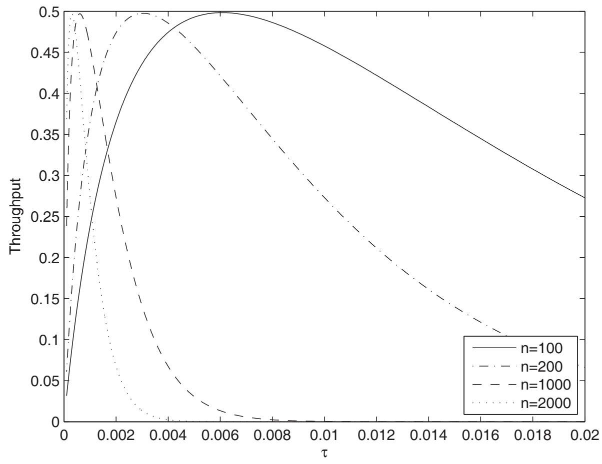

Fig. 5. Saturation throughput versus τ

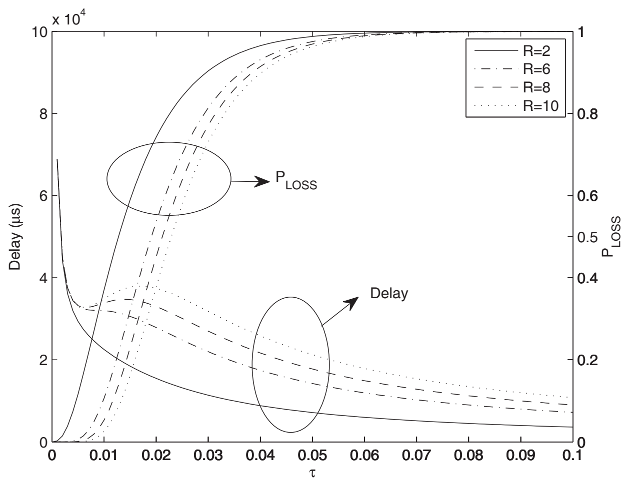

Fig. 6. Average access delay and P_{LOSS} versus τ with $n = 100$

The frame is ultimately dropped as it collides in backoff stage R, and we have $P\{LOSS \mid s = i\} = p^{R+1-i}$. Thus we obtain

$$P\{LOSS\} = \sum_{i=0}^{R} \frac{1-p}{1-p^{R+1}} p^{R+1} = \frac{(R+1)(1-p)}{1-p^{R+1}} p^{R+1} \tag{29}$$

By eq.(27) and eq.(29), we have the average delay

$$D = \frac{N}{\alpha} \frac{1}{1-p} T_{slot} \left(1 - \frac{(R+1)(1-p)}{1-p^{R+1}} p^{R+1}\right) \tag{30}$$

in which T_{slot} is the average time of a time slot. We can see that, although the retry limit R does not affect the transmission probability τ and throughput S, it will influence the average access delay D.

IV. Numerical Results

In this section, all MAC and PHY system parameters apply the settings in [8] with basic access scheme, in which the RTS/CTS scheme is not adopted. T_c is $179.64\mu s$, T_s is $179.64\mu s$, and δ is $50\mu s$.

Figure 4 plots the throughput versus the number of contending STAs. We find that when the contending STAs are few, the throughput increases with the number of STAs; however, when the number of contending STAs is large, the throughput decreases as n increases. Since the energy cost for a transmission is far greater than the harvesting rate, the transmission probability τ is relatively small because the STAs must spent much time recharging after a transmission. Consider a series of N time slots, when $n \ll N$, there are only n time slots will be busy in the worst case because a STA can only make one transmission in N time slots. Thus, either P_b or P_s is small when the contending STAs are few and then make the throughput increases with n. Nevertheless, when n is large, the probability that the channel is busy increases and a transmission is more likely to be collided, and thus the throughput decreases. The saturation throughput will reach a maximum when the number of contending STAs is about few hundreds to a thousand, depending on the energy harvesting parameters α and N. We find this result similar to the topic of Machine Type Communications (MTC) owing to its low transmission probability τ, and we suggest that in later works MTC could be combined with the idea of this paper.

Figure 5 shows the throughput versus the transmission probability τ. Similar to Fig. 4. When τ is small, both P_b and P_s are small, thus the denominator of (18) is dominated by $(1 - P_b)\delta$. However when τ is large, P_b becomes large but P_s is still small because the collision probability increases. We are able to follow the numerical method mentioned in last section to determine the energy harvesting parameters that gives maximum throughput. We can see that for larger systems with many STAs, the throughput curves drop suddenly after reach the maximum value. Our interpretation is that the collision probability rises rapidly in the system. In such a case, the transmission probability τ should be designed smaller and more accurate. Besides, we also find that the scale of system does not practically affect the maximum value of the system throughput as the derivation in the last section.

Figure 6 plots the average access delay D and P_{LOSS} versus transmission probability τ with $n = 100$. When transmission probability τ is small, devices takes most time accumulating energy and thus delay is large. As τ increases, more packets would be sent to the network, leading to more collision events and less packet waiting time. Observe that given a specific τ, larger retransmission times lead to larger delay (more random backoff time) for those successful packets, but less packet loss probability.

V. Conclusion

Energy harvesting has been addressed as an important technology in the development of advanced green technology, but the studies on the IEEE 802.11 network involved with energy harvesting devices have not yet supplied. To model devices with energy harvesting capability, a modified Markov Chain is constructed to integrate backoff window and recharging states. We address the characteristics of the modified DCF for an energy harvesting network, which include that (1) Transmission probability is quite small, dominated by the energy harvesting rate and transmission power, and is regardless of the retransmission limit. (2) With small transmission probability, numerous energy harvesting devices can coexist without severe collision. (3) Larger retransmission limit leads to higher average delay, lower packet loss ratio, but has no effect on throughput. These characteristics are quite different from that of classic IEEE 802.11 DCF, and we suggest that a dedicated version of IEEE 802.11 for energy harvesting network should be addressed in the future.

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