Analysis of the Multi-channel MAC Protocols in Wireless Networks

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***Abstract*—This paper discusses the problems that may be encountered in a multi-channel MAC protocol design. Furthermore, the normalization network throughput of multi-channel MAC is analyzed based on a Markov chain model. The simulation shows that compared to single channel 802.11, multi-channel MAC can improve the normalization network throughput. Moreover, the greater is the number of divided sub-channels, the higher is the normalization network throughput.**

Keywords- wireless networks, multi-channel MAC, IEEE 802.11, normalization throughput

I. INTRODUCTION

IEEE 802.11 based wireless networks are rapidly developing with an increasing number of applications that desire for higher capacity transmission. However, the IEEE 802.11 distributed coordination function (DCF) performs poorly under heavy traffic load environments, just as intrinsic high collision probability and unfairness access.

To relieve the drawbacks of single channel 802.11 protocol, the research community has been addressing the multi-channel protocols by two different approaches. One is a fixed-width channelization approach [1-11]. Among these multi-channel MAC protocols, the channelization structure is pre-configured that the entire available spectrum is divided into sub-channels with equal channel width, which is difficult to naturally adapt to temporal disparity in the traffic demands of nodes. Consequently, another variable-width channelization approach [12-19] has been addressed in the last few years. For further detailed analysis of the abovementioned multi-channel MAC protocols readers are referred to [20].

Our goal in this paper is to discuss the multi-channel problems and analyze the normalization network throughput of multi-channel MAC.

The rest of this paper is organized as follows. Section II discusses the problems that may be encountered in a multi-channel MAC protocol design. Section III analyzes the normalization network throughput of the single and multi-channel MAC based on a Markov chain model. Section IV concludes this paper.

II. MULTI-CHANNEL PROBLEMS

In this section, we discuss the problems that may be encountered in a multi-channel MAC protocol design.

A. Multi-channel hidden terminal

A node is called a multi-channel hidden terminal [1] if it interferes with one of its neighbors by attempting a transmission after switching to the same channel that this neighbor is currently using. This problem occurs due to the fact that one transceiver can only work on one channel at a time and hence a node is not aware of channel activities utilized by neighbor nodes.

B. Deafness problem

The deafness problem [3] occurs when a node continuously attempts to contact another node that is busy on a different channel. This will cause the attempt fail. For the IEEE 802.11 CSMA/CA mechanism, this means that the contact will be retried after a backoff until the maximal number of retrials expires. Also, it is indeed possible that the intended receiver finishes its current communication; however, the transmitter remains waiting for the backoff timer to expire. By the time the transmitter attempts the next retry, the receiver had switched to another channel for communication.

C. Control channel bottleneck

Consider a network where there are one dedicated control channel and N data channels. Let T_n and T_d respectively denote the average time to complete negotiations on the control channel and data exchange on the data channel for a transmitter-receiver pair. T_n consists of the backoff time and the time to exchange control frames (e.g. RTS and CTS frames), and T_d is the time to exchange data and ACK frames. If $T_n < T_d$, there are a maximum of $\lceil T_d / T_n \rceil$ transmitter-receiver pairs being able to complete negotiations on the dedicated control channel during time T_d, where $\lceil \cdot \rceil$ represents the largest integer that is less than or equal to the argument. And hence the channel bound for data channels is $\lceil T_d / T_n \rceil$, which means that the control

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$$b_{0,0}=\begin{cases}\dfrac{2(1-2p)\cdot(1-p)}{W\cdot(1-(2p)^{m+1})\cdot(1-p)+(1-2p)\cdot\left(1-p^{m+1}\right)}, m\le m' \\ \dfrac{2(1-2p)\cdot(1-p)}{W\cdot(1-(2p)^{m'+1})\cdot(1-p)+(1-2p)\cdot\left(1-p^{m+1}\right)+W\cdot 2^{m'}\cdot p^{m'+1}\cdot(1-2p)\cdot\left(1-p^{m-m'}\right)}, m>m'\end{cases} \quad (3)$$

channel might be the bottleneck when the data channels are more than a threshold [5, 11].

III. NORMALIZATION NETWORK THROUGHPUT OF MULTI-CHANNEL MAC

In this section, we analyze the normalization network throughput of multi-channel MAC based on a Markov chain model [21], taking finite retry limits into account as [22].

A. *Markov chain model*

IEEE 802.11 DCF adopts a binary exponential backoff scheme. At each packet transmission, the backoff time is uniformly chosen in the range $(0, CW-1)$. The value of CW depends on the number of failed transmissions of a packet. At the first transmission attempt $W = CW_{\min}$, which is the minimum contention window. After each retransmission due to a collision, CW is doubled up to a maximum value, $W_{m'} = CW_{\max} = 2^{m'} \cdot CW_{\min}$, where m' represents the maximum backoff stage and $W_{m'}$ is the largest contention window size. Once the CW reaches $CW_{\max}$, it will remain at the value until it is reset. Therefore, we have:

$$\begin{cases} W_i = 2^i W, & i \le m' \\ W_i = 2^{m'} W, & i > m' \end{cases} \quad (1)$$

where i is the backoff stage, $i \in (0, m)$ and m represents the maximum retransmission limits.

Let $b(t)$ be the stochastic process representing the backoff time counter for a given node and $s(t)$ be the stochastic process representing the backoff stage $(0,\ldots,m)$ of the node at time t. So we model the bidimensional process $\{s(t), b(t)\}$ with the discrete-time Markov chain depicted in Fig.1.

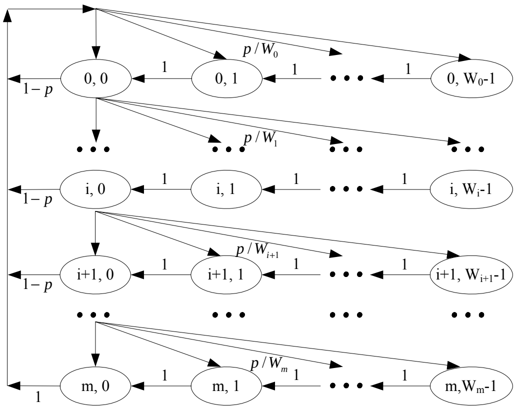

Figure 1. Markov chain model

Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\}$, $i \in (0, m)$, $k \in (0, W_i - 1)$ be the stationary distribution of the Markov chain. It is assumed that each packet collides with constant and independent probability p . As any transmission occurs when the backoff time counter reaches zero, the probability τ that a node transmits a packet in a randomly chosen slot time can be expressed as [21,22]:

$$\tau = \sum_{i=0}^{m} b_{i,0} = \sum_{i=0}^{m} p^i \cdot b_{0,0} = b_{0,0} \cdot \frac{1-p^{m+1}}{1-p} \quad (2)$$

where $b_{0,0}$ is given by (3). From (2), we can see that the transmission probability τ depends on the collision probability p. The probability p that a transmitted packet encounters a collision is the probability that at least one of the $(n-1)$ remaining nodes transmit in the same time slot. If all nodes transmit with probability τ , the collision probability p is:

$$p = 1-\left(1-\tau\right)^{n-1} \quad (4)$$

Therefore, (2) and (4) form a nonlinear system with two unknowns τ and p , which can be solved by numerical method. Note that $p \in (0,1)$ and $\tau \in (0,1)$.

B. *Normalization network throughput*

Let P_{tr} be the probability that there is at least one transmission in the considered slot time. When n nodes contend on the same channel and each transmits with probability τ :

$$P_{tr} = 1-\left(1-\tau\right)^{n} \quad (5$$

The probability P_{s} that an occurring packet transmission is successful is given by the probability that exactly one node transmits and the remaining $(n-1)$ nodes defer transmission, conditioned on the fact that at least one node transmits:

$$P_s = \frac{n\tau\left(1-\tau\right)^{n-1}}{P_{tr}} = \frac{n\tau\left(1-\tau\right)^{n-1}}{1-\left(1-\tau\right)^{n}} \quad (6)$$

1) Normalization network throughput of single channel 802.11

Considering that a random slot is empty with probability $(1-P_{tr})$, contains a successful transmission with probability $P_{tr}P_s$ and a collision with probability $P_{tr}\left(1-P_s\right)$, the normalization network throughput of the single channel 802.11 protocol is given by:

$$S_{single} = \frac{P_s P_{tr} T_{payload}}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}\left(1-P_s\right)T_c} \quad (7)$$

where $T_{payload}$ represents the transmission time of payload, T_s is the average time that the channel is sensed busy due to a successful transmission, T_c is the average time that the channel is sensed busy by each node during a collision, and σ is the duration of an empty slot time. The values of T_s and T_c depend on the channel access mechanism of IEEE 802.11 and for the basic access mechanism:

$$T_s^{rts} = T_{DIFS} + T_H + T_{payload} + T_{SIFS} + T_{ACK} \tag{8}$$

$$T_c^{rts} = T_{DIFS} + T_H + T_{payload} + T_{SIFS} + T_{ACK} \tag{9}$$

where T_H represents the transmission time of packet header ($H = MAC_{hdr} + PHY_{hdr}$) and hence (7) can be expressed as:

$$S_{\sin gle} = \frac{P_s P_{tr} T_{payload}}{(1-P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}\left(1-P_s\right)T_c} = \frac{P_s P_{tr} T_{payload}}{(1-P_{tr})\sigma + P_{tr} T_s} \tag{10}$$

2) Normalization network throughput of multi-channel MAC

If one channel is divided to k sub-channels, there are n/k nodes to compete at each sub-channel, therefore,

$$P_{tr}(k) = 1-(1-\tau)^{n/k} \tag{11}$$

$$P_s(k) = \frac{(n/k)\tau(1-\tau)^{(n/k)-1}}{P_{tr}(k)} \tag{12}$$

Owing to the sub-channel bandwidth reduces to $1/k$ of the original channel, given the same channel coding and signal modulation mode as before, the data transmission rate reduces to $1/k$, that is to say, the transmission time that transmit the same packet increases to k times , therefore, the normalization throughput of each sub-channel is:

$$S(k) = \frac{P_{tr}(k)P_s(k)kT_{payload}}{(1-P_{tr}(k))\sigma + P_{tr}(k)kT_s} \tag{13}$$

(i) $k \le n$

The normalization network throughput is equal to the normalization throughput of sub-channel, i.e. $S(k)$.

(ii) $k > n$

There are most n nodes transmitting at the same time and hence there are $(k-n)$ sub-channels are idle, therefore, the normalization network throughput is $S(k)\cdot\frac{n}{k}$.

C. Numerical results

According to (10) and (13), we compare the normalization network throughput achieved by multi-channel MAC with that achieved by the single channel 802.11 protocol, through 1000 times Monte Carlo simulations. The main parameters are listed in Table I based on IEEE 802.11g standard.

TABLE I. PARAMETERS USED IN SIMULATIONS

Parameters	values
payload	1024 bytes
MAC/PHY header	28/24 bytes
ACK	38 bytes
SIFS/ DIFS/ Slot time	16/50/9 μ s
aCWMin /aCWMax	15/1023 slots
m / m'	7/5

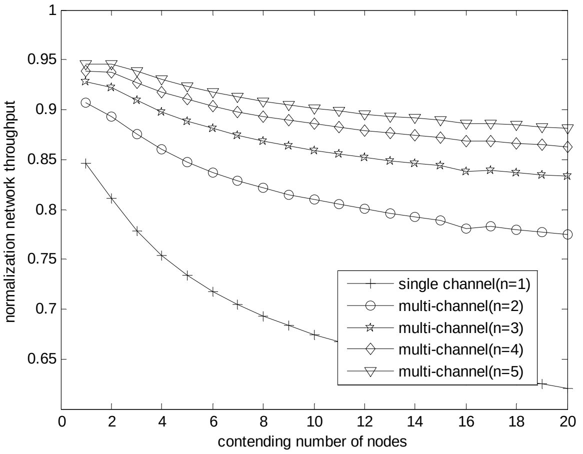

Figure 2. Normalization network throughput of single channel 802.11 and multi-channel MAC

Fig.2 depicts the normalization network throughput of single channel 802.11 and multi-channel MAC varying with the contending number of nodes. The graph shows that: when one given channel is divided into multiple sub-channels, compared to single channel 802.11, multi-channel MAC can improve the normalization network throughput. Moreover, the greater is the number of divided sub-channels, the higher is the normalization network throughput. However, as the number of sub-channel increases, the increased range of network performance decreases.

It is also shown that, as number of contending nodes increases, the normalization network throughput of multi-channel MAC and single channel 802.11 both decrease. This is due to the fact that as the number of contending nodes increase, the collision probability becomes higher, which greatly affects network performance. However, the multi-channel MAC always significantly outperforms the single channel 802.11.

IV. CONCLUSIONS

This paper firstly discusses the problems that may be encountered in a multi-channel MAC protocol design in the wireless networks, i.e. the multi-channel hidden terminal, deafness problem and control channel bottleneck; then analyze the normalization network throughput of multi-channel MAC based on a Markov chain model. The simulation shows that when one given channel is divided into multiple sub-channels, compared to single channel 802.11, multi-channel MAC can improve the normalization network throughput. Moreover, the greater is the number of divided sub-channels, the higher is the normalization network throughput. However, as the number of sub-channel increases, the increased range of network performance decreases.

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