Performance analysis and saturation bound research of cyclic-quorum multichannel MAC protocol based on Markov chain model

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Abstract

In high diversity node situation, single-channel MAC protocols suffer from many collisions. To solve this problem, the research of multichannel MAC protocol has become a hotspot. And the cyclic quorum-based multichannel (CQM) MAC protocol outperformed others owing to its high frequency utilization. In addition, it can avoid the bottleneck that others suffered from and can be easily realized with only one transceiver. To obtain the accurate performance of CQM MAC protocol, a Markov chain model, which combines the channel hopping strategy of CQM protocol and IEEE 802.11 distributed coordination function (DCF), is proposed. The metrics (throughput and average packet transmission delay) are calculated in performance analysis, with respect to node number, packet rate, channel slot length and channel number. The results of numerical analysis show that the optimal performance of CQM protocol can be obtained in saturation bound situation. And then we obtain the saturation bound of CQM system by bird swarm algorithm (BSA). Finally, the Markov chain model and saturation bound are verified by Qualnet platform. And the simulation results show that the analytic and simulation results match very well.

Keywords: multichannel MAC protocol; CQM protocol; Markov chain model; saturation bound; bird swarm algorithm

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1. Introduction

As an important MAC protocol, the IEEE 802.11 Distributed Coordination Function (DCF)[1] has been widely used in mobile ad hoc networks. However, in high diversity node situation, the IEEE 802.11 DCF suffers from many collisions, resulting in low frequency utilization[2].

To solve this problem, multichannel MAC protocol has become a hotspot recently[3][4]. And utilizing multiple channels may help in sharing traffic loads among different channels. Allowing users to use multiple channels can also increase spatial reuse, which increases the aggregate throughput of network. In fact, IEEE 802.11b and IEEE 802.11a can support 3 and 13 non-overlapping channels, respectively[2]. This means that designing a multichannel MAC (MMAC) protocol is feasible and desirable in IEEE 802.11-based mobile ad hoc networks.

Although some MMAC protocols([5]-[10]), equipped with at least two transceivers, can increase throughput, it really raises certain disadvantage of high hardware cost. Hence, we only discuss single-transceiver protocols in the rest of paper.

Rendezvous problem and missing receiver problem are main problems encountered in designing single-transceiver MMAC protocol. The situation that at most one transmission pair can be handled at one moment, is called rendezvous problem. In some MMAC protocols([11]-[13]), rendezvous problem occurs, and the dedicated control channel or common control period are bottleneck of the network throughput. Although rendezvous problem can be solved in several protocols([14]-[16]), missing receiver problem plays disadvantage in improving network performance. In these protocols, missing receiver problem frequently occurs, particularly in a heavy-loaded environment.

To overcome existing problems above, a cyclic quorum-based multichannel (CQM) MAC protocol, with IEEE 802.11DCF adopted, is proposed in reference[2]. Owing to the elegant feature of rotation closure property of the cyclic quorum system, every channel has the same chance to be accessed. And simulation and real system implementation results show that CQM protocol outperforms the existing slotted seeded channel-hopping (SSCH) MAC protocol[14] and multichannel MAC (McMAC) protocol[15].

However, the performance of CQM protocol is only analyzed and compared by simulation in reference [2]. Since simulation has several limitations, we analyze the performance of CQM protocol theoretically. In this way, the performance advantages and the most optimal performance of CQM protocol, with IEEE 802.11 DCF adopted, can be well revealed

Plenty of researches have been carried out on the performance evaluation of IEEE 802.11 protocol based on Markov chain model([17]-[19]). Bianchi et al. in [17] introduced the 2-dimensional Markov chain model to analyze the saturation throughput of IEEE 802.11. Nguyen et al. in [18] analyzed the performance of IEEE 802.11 with saturated and unsaturated source. Weng et al. in [19] built the model of IEEE 802.11 DCF with Optimal contention window, taking account of the freezing of the back-off counter when channel is busy. Although only a single shared channel is considered in these Markov models, this motivates us to develop an analytical model based on Markov chain. Meanwhile, several researches([20]-[22]) analyzed the performances of multichannel mac protocols theoretically, based on Markov model. Kao et al. in [20] proposed an analytical model to compute the throughput of dedicated control channel protocols, and a novel multi-channel MAC protocol was also proposed to improve network throughput. Dang et al. in [21] proposed a hybrid multi-channel MAC protocol, with IEEE 802.11 PSM adopted. The performance was also analyzed theoretically based on Markov model. Yan in [22] proposed analytical model and deduced the normalized throughput formula to analysis the performance of dedicated control channel multichannel protocol. Although these theoratical analysis focused on dedicated control channel pattern and common control period pattern, which didn't suit to CQM protocol, they also provided ideas for theoretical analysis of CQM protocol.

Based on this background, this study aims to analysis the performance of CQM protocol through mathematical modeling and get the saturation bound, at which the CQM protocol can reach its most optimal performance. In particular, the main contributions of this paper are as follows:

1). The mathematical model of CQM protocol is proposed, based on Markov chain. The Markov model is obtained by combining channel hopping stratege of CQM protocol and IEEE 802.11 DCF.

2). Based on Markov model, the relationships between metrics(throughput and average packet transmission delay) and variables(channel number, the node number, the packet rate and channel slot length) are revealed. And the saturation bound phenomenon of CQM protocol is found through numerical analysis.

3). The saturation bound condition of CQM protocol is obtained by using bird swarm algorithm (BSA)[23], at which CQM protocol can reach its most optimal performance.

4). The Markov chain model and saturation bound are verified by simulating on Qualnet platform. The results show that simulation results match well with analytical results.

The rest of this paper is organized as follows. Section 2 reviews related work on MMAC protocols in ad hoc networks. And the cyclic quorum system and CQM protocol are described. The Markov chain model of CQM protocol and state steady probabilities of a node are given in section 3. The metrics(throughput and average packet transmission delay) are calculated and the saturation bound phenomenon of CQM system is found by numerical analysis in section 4. Section 5 gets the saturation bound by using bird swarm optimal algorithm. In addition, simulation results validating the model are given in Section 6. The paper is concluded in Section 7.

2. Related work

The great challenge of designing MMAC is how to allocate channels to node for transmitting information. And solutions with one transceiver to this problem can be classified into two patterns as follows:

a. channel negotiating pattern: channels allocated by negotiating through dedicated control slot or channel

b. channel hopping pattern: nodes switch channels in a fixed pattern or random mechanism

There are many protocols ([11]-[13]) that belong to the channel negotiating pattern. Dang et al. in [11] propose a Multi-channel MAC protocol with directional antennas (MMAC-DA) that adopts IEEE 802.11 power saving mechanism (PSM) and exploits multiple channel resources and directional antennas. Chen et al. in [12] proposed a distributed asynchronous reservation MAC(DARMAC) protocol. In this protocol, nodes share their information about network space in a dedicated control channel and cooperatively select a collision free channel for the node that wants to transmit. Cetinkaya in [13] proposed a novel and efficient control-channel-based, multi-channel mechanism that used a single transceiver. Rendezvous problem occurs in these protocols, since a dedicated control channel or a common control period is used for control message exchange. And the dedicated control channel and common control period will be the bottleneck of the performance of network, if the capacity of the dedicated control channel and the data channels is not properly distributed.

Different from the channel negotiating pattern, some other solutions utilize the channel-hopping concept to switch among data channels to achieve concurrent handshaking. The protocols([14][16]) are equipped with only one transceiver. In these protocols, different nodes have different channel-hopping sequences, and each pair of nodes is able to communicate with each other when they switch to the same channel at the same time slot. In the SSCH protocol[14], a channel-hopping mechanism is proposed such that any two nodes are guaranteed to have a rendezvous once in one cycle. In reference [15], a multichannel protocol, called McMAC protocol, uses a common linear congruential generator to build each node's channel-hopping sequence. An asynchronous efficient multichannel MAC (EM-MAC) protocol also adopts the pseudo random channel-hopping mechanism in [16]. A flaw of these channel-hopping protocols is that they may suffer from the missing receiver problem. This problem frequently occurs, particularly in a heavy-loaded environment.

In reference [2], Chao proposed a CQM protocol, based on cyclic quorum system. Owing to the elegant feature of rotation closure property of the cyclic quorum system, every channel has the same chance to be accessed. Hence, it can overcome the bottleneck of channel negotiating pattern and the missing receiver problem of channel hopping pattern. The overviews of cyclic quorum system and CQM protocol will be described as follow.

2.1 Cyclic quorum system

Quorum systems have been widely used for MAC protocol designing in wireless networks [24][25]. And a quorum system can be defined as follows.

Given a universal set $U=\{0,\cdots,n-1\}$, a quorum system Q under U is a collection of nonempty subsets of U, each called a quorum, which satisfies the intersection property,

$$\forall G,H\in Q: G\cap H\neq\phi \tag{1}$$

There are many quorum systems, such as the cyclic quorum system, the grid quorum system, and the torus quorum system. The cyclic quorum system has the elegant feature of rotation closure property, and it can provide equal opportunity for a node to transmit and to receive. The rotation closure property is as follows:

$$\begin{aligned}&\forall G,H\in Q, i\in\{0,\cdots,n-1\}: G\cap rotate(H,i)\neq\varnothing\\&where\quad rotate(H,i)=\{(j+i)\bmod n \mid j\in H\}\end{aligned} \tag{2}$$

A cyclic quorum system can be constructed from a difference set. The definitions of a difference set and a cyclic quorum system are as follows.

Given a set $D=\{d_1,\cdots,d_k\}, d_k\in Z_n$, The set D can be a difference set if :

$$\begin{aligned}&\forall(e\neq 0)\bmod n,\\&\exists(d_i-d_j)=e\bmod n\quad where\quad d_i,d_j\in D\end{aligned} \tag{3}$$

Given a difference set $D=\{d_1,\cdots,d_k\}, d_k\in Z_n$, and then a cyclic quorum Q can be defined as follow :

$$Q=\{Q_0,\cdots,Q_{n-1}\},\quad where\quad Q_i=\{d_1+i,\cdots,d_k+i\}\bmod n,\quad i=1,\cdots n \tag{4}$$

2.2 CQM Protocol

Based on cyclic quorum system, Chao proposed CQM protocol[2]. The CQM protocol don't need channel negotiating, so the bottleneck of channel negotiating mechanism can be avoided. In CQM protocol, nodes can communicate with others when they meet at the same channel and same channel slot. And it can provide equal opportunity for nodes to transmit and to receive based on the cyclic quorum system.

In CQM protocol, time is divided into a series of cycles. Each cycle consists of default channel slots and switching channel slots, numbered from 0 to $z-1$. The value of z is determined by the integer set from which the adopted difference set is derived. According to reference[2], CQM system performs better under Z_6. In this paper, Z_6 is adopted in the analysis of CQM system.

Let T denotes the channel slot length, to separate with system time slot σ. We assume that the length of channel slot T is long enough to transmit at least one data packet. At default channel slots, a node stays at its default channel, waiting for transmission requests. At switching channel slots, a node may switch to its intended receiver's default channel. We use a cyclic quorum G_i under Z_n to identify a node's default slots. Specifically, for any node $i \in V$, where V is the set of nodes in the network, ith node's default channel (denoted as DC_i) and default slots (denoted as DS_i) are chosen as follows:

$$\begin{aligned} &DC_i = node\_ID_i (\bmod h) \\ &DS_i = G_j, j = node\_ID_i (\bmod z), where \quad i \in V \end{aligned} \tag{5}$$

where $node\_ID_i$ is the ID of ith node.

Fig. 1 is an example of CQM operation under Z_6 with two channels (numbered from 0 to 1). Nodes 0, 1 and N, with IDs 0, 1 and N, respectively, are within each other's transmission range. Each node's default channel and default slots are shown in **Fig. 1**, supposing that we choose the difference set $\{0, 1, 3\}$ under Z_6 as G_0. The marked time slots are default channel slots. The number in each channel slot is the channel that should be switched to.

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As is shown in **Fig. 1**, when a packet arrives at a random time slot, the packet should wait in queue until all preceding packets are transmitted. And then the node looks up its channel hopping table and checks whether it can meet its destination node at the current channel slot. If they meet each other at the current channel slot, the node can turn into the back off stage. Otherwise, the node will turn into $Wait^1$ state to wait for the next channel slot available. During back off stage, the back off timer of a node is set to a random time according to IEEE 802.11 DCF scheme. In this paper, according to CQM protocol, when the channel is occupied by the other nodes or the current channel slot is empty, the back off timer is assumed to be held to wait for the next channel slot available. And then, the channel slot remaining will be checked when back off timer reaches zero. If the channel slot remaining is long enough for one packet transmission, the packet will be transmitted. Otherwise, the node should turn into $Wait_{i,0}^{3}$ state to wait for the next channel slot available. Finally, after each successful transmission or after having reached the maximum number of the retransmissions m, if there is a packet to be transmitted in queue, the node enters into checking processing again.

Otherwise, the node enters into the *Idle* state. q denotes the probability of having an empty queue.

Take Node 0 for example, **Table 1** shows average channel slots needed between twice meeting in one cycle in the situation that the node is at meeting state and waiting state. And the average meeting slots and waiting slots in one cycle are also shown in **Table 1**.

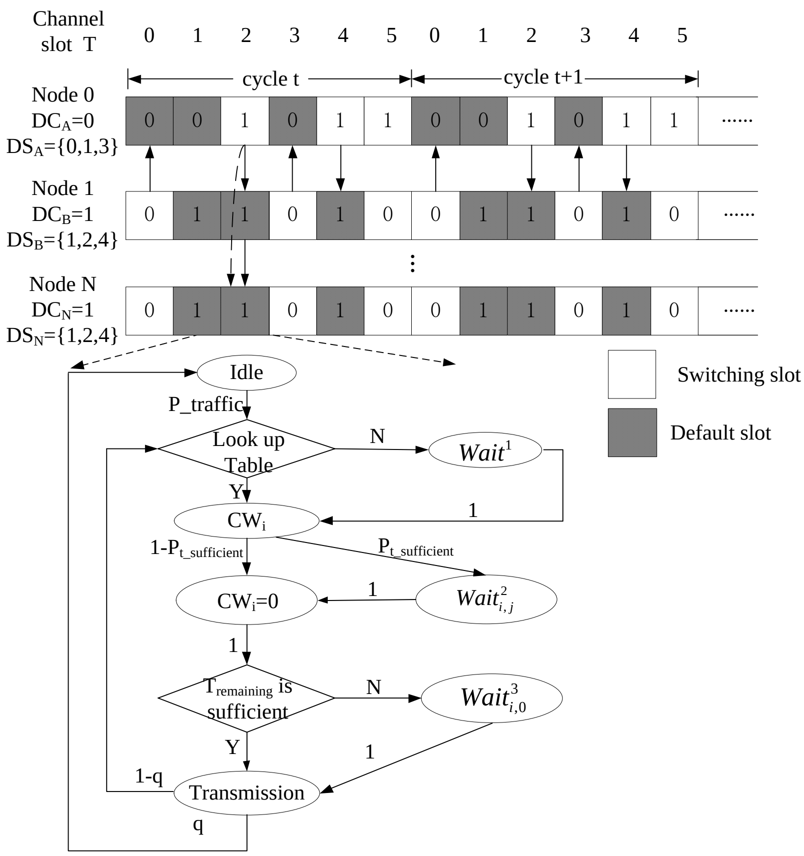


Fig. 1. The protocol processing of CQM protocol with two channels

Table 1. Average channel slots analysis of node 0

Quroum Combinations	Waiting channel slots between two meeting: Meeting state	Waiting channel slots between two meeting: Waiting state	channel slots in one cycle: Meeting slots	channel slots in one cycle: Waiting slots
G_0+G_0	1/h	4/3h	3/h	(6h-3)/h
G_0+G_1	2	7/4	2	4
G_0+G_2	2	2	2	4
G_0+G_3	6	3	1	5
G_0+G_4	3	5/2	2	4
G_0+G_5	2	3/2	2	4
Results	E(W_meeting) $\frac{15h+1}{6h}$	E(W_waiting) $\frac{129h+16}{12h}$	E(M_slots) $\frac{3h+1}{2h}$	E(W_slots) $\frac{9h-1}{2h}$

3. Markov chain model for CQM protocol

Combined the channel hopping strategy of CQM protocol and IEEE 802.11 DCF, the Markov chain model of CQM protocol is proposed, as is shown in **Fig. 2**. We consider the following assumptions for modeling network: (1) The network consists of n nodes moving in the range of transmission distance, and packets are transmitted from sources to destinations directly. (2) A total of h channels are available for every node, and all of them have the same bandwidth. (3) Every node knows the IDs of its one-hop neighbors, and every node is equipped with one half-duplex transceiver, which is able to switch to any channel dynamically. (4) Every node are time synchronized, and use the IEEE 802.11 DCF (RTS/CTS mode) as MAC protocol. (5) Packets arrive to a node according to a Poisson process with rate λ packets/s. (6) The channel is assumed to be error-free. Packet transmission is considered to be successful if there are no other packets transmissions at the same time.

According to CQM protocol, each node has the same chance to transmit packet through different channels. So we can take one selected channel of a node into consider to model the CQM protocol scheme at MAC layer. And then we assume that there are $n' = n/h$ nodes with packets rate λ to content in one selected channel in a random time slot. The model consists of states that a node can reside in. The points $C_0, C_1, C_2, C_0', \cdots, C_m'$ represent connection points, which are not states.

During queuing stage, the arriving packet will wait in buffer, if there are other packets to be transmitted. And if there is no packet in buff, the node will turn into $Idle$ state.

If the packet is eligible to be transmitted, the node enters into checking stage. The channel hopping table will be checked firstly. The node can meet its destination node with probability $P_{meeting}$, and turns into $Wait^1$ state to wait for next channel slot available with probability $1-P_{meeting}$.

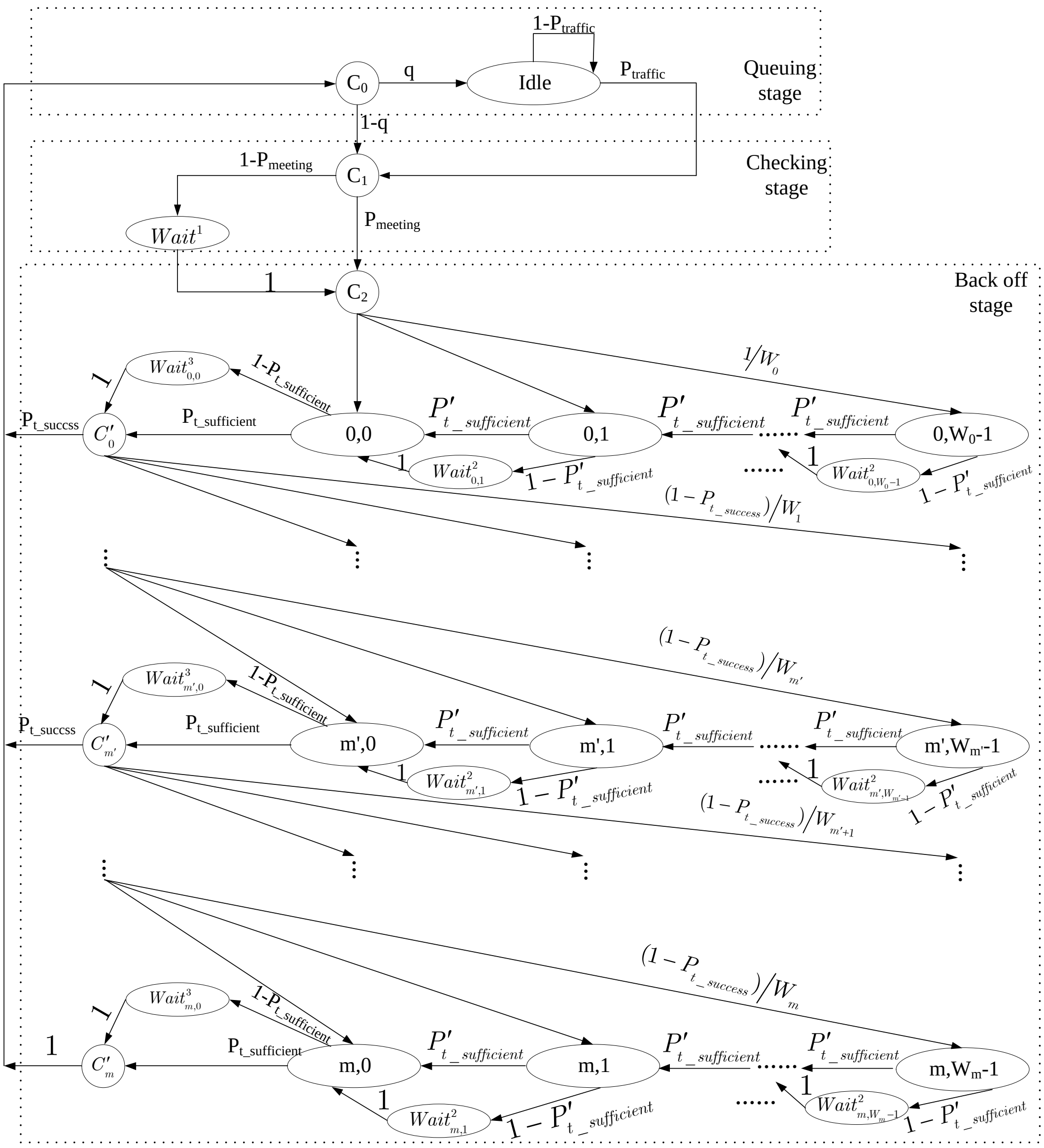


Fig. 2. Markov chain model of CQM protocol

During back off stage, we use the tuple (i,k) to represent the different states. i denotes the ith back off stage, number $i=0,1,\cdots,m',\cdots,m$, and k denotes the value of back off timer in the range $[0,W_i-1]$ [26]. W_i is the size of the CW at stage i, which can be expressed as follow:

$$W_i=\begin{cases}2^iW_0, & if \quad i\le m' \\ 2^{m'}W_0, & if \quad i>m'\end{cases} \tag{6}$$

where m denotes the maximum number of packet retransmissions before the packet is dropped. According to reference [27], the default value for m' is 5 and it is 7 for m.

When time slot σ is idle and the current channel slot remaining is sufficient for once back off timer decrease, the state (i,k) will turn into $(i,k-1)$ with probability $P'_{t\_sufficient}$. Otherwise, the back off timer will be held and the node will wait for next channel slot available.

According to 802.11 DCF, the packet will be transmitted when node turn into $(i,0)$ states. Different from that, in this model, only if channel slot remaining is long enough for one packet transmission, the packet will be transmitted at $(i,0)$ states. Otherwise, the node will enter into $Wait^3_{i,0}$ state to wait for next channel slot available. $P_{i,k}$ denotes the probability of state (i,k). $P_{t\_success}$ denotes the probability that a node transmits successfully in a random time slot and one selected channel. Let P_{C_i} denotes the probability that the node arrives at point C_i.

In order to obtain the expression of state steady probabilities of a node, firstly, we need to express $P_{i,k}$ in terms of $P_{0,0}$. According to **Fig. 2**, during back off stage, we can obtain the following relations:

$$\begin{aligned} P_{C'_i} &= P_{i,0}P_{t\_sufficient} + P_{Wait^3_{i,0}} \\ &= P_{i,0}P_{t\_sufficient} + P_{i,0}(1-P_{t\_sufficient}) = P_{i,0} \quad ,0 \le i \le m \\ P_{i,k} &= P_{i,k+1}P'_{t\_sufficient} + P_{Wait^2_{i,k}} \\ &= P_{i,k+1}P'_{t\_sufficient} + P_{i,k+1}(1-P'_{t\_sufficient}) = P_{i,k+1} \quad ,0 \le j \le W_i - 1 \end{aligned} \tag{7}$$

$$P_{i,0} = \begin{cases} \sum_{u=0}^{w_i-1} P_{C'_{i-1}} \dfrac{1-P_{t\_success}}{w_i} = (1-P_{t\_success})^i P_{0,0}, & 1 \le i \le m \\ \sum_{u=0}^{w_0-1} P_{C_2} \dfrac{1}{w_0} = P_{C_2}, & i = 0 \end{cases} \tag{8}$$

$$P_{i,k} = \begin{cases} \sum_{u=0}^{w_i-k-1} P_{C'_{i-1}} \dfrac{1-P_{t\_success}}{w_i} = \dfrac{w_i-k}{w_i}(1-P_{t\_success})^i P_{0,0}, & 1 \le i \le m \\ \sum_{u=0}^{w_0-k-1} P_{C_2} \dfrac{1}{w_0} = \dfrac{w_0-k}{w_0} P_{C_2} = \dfrac{w_0-k}{w_0} P_{0,0}, & i = 0 \end{cases} \tag{9}$$

where $P_{t\_sufficient}$ and $P'_{t\_sufficient}$ denotes the probability of that the channel time remaining is enough for one packet transmission and once back off timer decrease respectively. They can be expressed as follow:

$$P_{t\_sufficient} = \frac{T-T_s}{T}, \quad P'_{t\_sufficient} = \frac{T-\sigma}{T} \tag{10}$$

Let P^s_r denotes the probability that only s nodes out of r nodes transmit packets in a random time slot and one selected channel. Hence, $P_{t\_success}$ can be expressed as follow:

$$P_{t\_success} = P^0_{n'-1} = C^0_{n'-1}(\tau)^0(1-\tau)^{n'-1} = (1-\tau)^{n'-1} \tag{11}$$

where τ denotes the probability that a node transmits one packet in a random time slot and one selected channel. τ can be expressed as follow:

$$\tau=\sum_{i=0}^{m}P_{C_i'}=\sum_{i=0}^{m}(1-P_{t\_success})^i P_{0,0}=\alpha P_{0,0},\quad where\quad \alpha=\frac{1-\left(1-P_{t\_success}\right)^{m+1}}{P_{t\_success}} \tag{12}$$

Combined equation (11) and (12), $P_{0,0}$ can be expressed with $P_{t\_success}$.

$$P_{0,0}=\frac{1-P_{t\_success}{}^{\frac{1}{n'-1}}}{\alpha} \tag{13}$$

And then, the P_{C_i} can be obtained as follow:

$$P_{C_0}=\sum_{i=0}^{m-1}P_{C_i'}P_{t\_success}+P_{C_m'}=\sum_{i=0}^{m-1}(1-P_{t\_success})^i P_{0,0}P_{t\_success}+(1-P_{t\_success})^m P_{0,0}=P_{0,0} \tag{14}$$

$$P_{Idle}=\frac{P_{C_0}q}{\mathrm{P}_{traffic}}=\frac{q}{\mathrm{P}_{traffic}}P_{0,0} \tag{15}$$

$$P_{C_1}=P_{C_0}(1-q)+P_{Idle}P_{traffic}=P_{C_0}=P_{0,0} \tag{16}$$

$$P_{C_2}=P_{C_1}P_{meeting}+P_{Wait1}=P_{C_1}P_{meeting}+P_{C_1}(1-P_{meeting})=P_{C_1}=P_{0,0} \tag{17}$$

where $P_{meeting}$ denotes the probability that a pair of nodes can meet each other in a random channel slot and a selected channel. According to analysis above, $P_{meeting}$ can be expressed as follow:

$$P_{meeting}=\frac{E(M\_slots)}{6}=\frac{3h+1}{12h} \tag{18}$$

Let P_{Wait^1}, $P_{Wait^2_{i,k}}$ and $P_{Wait^3_{i,0}}$ denotes the probability of $Wait^1$, $Wait^2_{i,k}$ and $Wait^3_{i,0}$ state respectively. T_{Wait^1}, $T_{Wait^2_{i,k}}$ and $T_{Wait^3_{i,0}}$ denotes the time cost at $Wait^1$, $Wait^2_{i,k}$ and $Wait^3_{i,0}$ state. According to **Fig. 2**, they can be expressed as follow:

$$\begin{aligned}
&P_{Wait^1}=P_{C_1}(1-P_{meeting})=\frac{9h-1}{12h}P_{0,0},\quad T_{Wait^1}=E(W_waiting)T=\frac{129h+16}{12h}T\\
&P_{Wait^2_{i,k}}=\frac{(W_i-k)(1-P_{t_success})^i\sigma P_{0,0}}{W_iT},\quad T_{Wait^2_{i,k}}=E(W_meeting)T=\frac{(15h+1)T}{6\mathrm{h}}\\
&P_{Wait^3_{i,0}}=\frac{(1-P_{t_success})^i P_{0,0}T_s}{T},\quad T_{Wait^3_{i,0}}=\frac{T_s}{2}+E(W_meeting)T=\frac{(15h+1)T+3hT_s}{6h}
\end{aligned} \tag{19}$$

where $P_{traffic}=1-e^{-\lambda\sigma}$ denotes the probability of having packet to be transmitted in a random time slot σ when the node is at $Idle$ state. q denotes the probability of that there is no packet in the queue of a node after each successful transmission or after having reached the maximum number of the retransmissions m. q can be expressed as follow:

$$q=e^{-\lambda E[S_b]} \tag{20}$$

And then equation (15) can be rewrite as follow:

$$P_{Idle} = \frac{q}{\mathrm{P}_{traffic}} P_{0,0} = \frac{q}{1-e^{-\lambda\sigma}} P_{0,0} \tag{21}$$

Where $E[S_b]$ denotes the average service time of one packet transmission (from the packet leaves the MAC buffer until it is successfully transmitted or reaches the retry limit). According to the **Fig. 2**, $E[S_b]$ includes two section: the one is the average time cost in checking stage ($E[T_{Wait^1}]$), the other is the average time cost in back off stage($E[T_{backoff}]$).

$$E[S_b] = E[T_{Wait^1}] + E[T_{backoff}] \tag{22}$$

According to **Fig. 2**, $E[T_{Wait^1}]$ can be expressed as follow:

$$E[T_{Wait^1}] = T_{Wait^1} P_{Wait^1} = \frac{(9h-1)(129h+16)T}{144h^2} P_{0,0} \tag{23}$$

To get the value of all states in **Fig. 2**, the average time cost $E[T_{backoff}]$ in back off stage should be obtained firstly. According to **Fig. 2**, $E[T_{backoff}]$ can be expressed as follow:

$$\begin{aligned} E[T_{backoff}] &= \bar{\sigma}\sum_{i=0}^{m}\left(1-P_{t\_success}\right)^i \frac{W_i-1}{2} + \sum_{i=0}^{m}\left(T_S + T_{Wait^3_{i,0}}\left(1-P_{t\_succicient}\right)\right)\left(1-P_{t\_success}\right)^i P_{t\_success} \\ &+ \sum_{i=1}^{m}\left(T_C + T_{Wait^3_{i,0}}\left(1-P_{t\_succicient}\right)\right)\left(\left(1-P_{t\_success}\right)^i P_{t\_success} i + (m+1)\left(1-P_{t\_success}\right)^{m+1}\right) \end{aligned} \tag{24}$$

Combined equation (6) with equation (24), $E[T_{backoff}]$ can be expressed with $P_{t\_success}$.

$$\begin{aligned} &E[T_{backoff}] \\ &= \frac{\bar{\sigma}}{2}\left(\frac{\left(1-\left(2(1-P_{t\_success})\right)^{m'+1}\right)W_0}{1-2(1-P_{t\_success})} + \frac{2^{m'}\left(1-P_{t\_success}\right)^{m'+1} W_0\left(1-\left(1-P_{t\_success}\right)^{m-m'}\right)}{P_{t\_success}} - \alpha\right) \\ &+ \left(T_S + \frac{(15h+1)TT_S + 3hT_S{}^2}{6hT}\right)\alpha P_{t\_success} \\ &+ \left(T_C + \frac{(15h+1)TT_S + 3hT_S{}^2}{6hT}\right)\left(1-P_{t\_success}\right)\alpha \end{aligned} \tag{25}$$

Assume $\beta = \frac{\left(1-\left(2(1-P_{t\_success})\right)^{m'+1}\right)W_0}{1-2(1-P_{t\_success})} + \frac{2^{m'}\left(1-P_{t\_success}\right)^{m'+1} W_0\left(1-\left(1-P_{t\_success}\right)^{m-m'}\right)}{P_{t\_success}}$, $\gamma = \frac{(15h+1)TT_S + 3hT_S{}^2}{6hT}$, and then the equation (25) can be rewritten as follow:

$$E[T_{backoff}] = \frac{\bar{\sigma}}{2}(\beta-\alpha) + (T_S+\gamma)\alpha P_{t\_success} + (T_C+\gamma)\left(1-P_{t\_success}\right)\alpha \tag{26}$$

where $\bar{\sigma}$ denotes the average time between successive counter decrements in back off stage. The time needed for successive counter decrements includes situations: only one time slot σ' needed when all the other nodes have no packet to be transmitted, $T_s+\sigma'$ needed when a packet is transmitted successfully by the other nodes, $T_c+\sigma'$ needed when a transmission collision occurs in the other nodes. Let $P_{\sigma'}$, $P_{T_s+\sigma'}$ and $P_{T_c+\sigma'}$ denote probabilities of these situations respectively. Where σ' denotes the average time cost for once back off timer decrease when the channel is idle. σ' can be expressed as follow:

$$\sigma' = \sigma P'_{t\_sufficient} + T_{Wait^2_{i,k}}\left(1-P'_{t\_sufficient}\right) = \frac{(T-\sigma)\sigma}{T} + \frac{(15h+1)\sigma}{6\text{h}} \tag{27}$$

And then, we can get:

$$\begin{aligned} P_{\sigma'} &= P^0_{n'-1} = (1-\tau)^{n'-1} \\ P_{T_s+\sigma'} &= P^1_{n'-1} = C^1_{n'-1}\tau(1-\tau)^{n'-2} = (n'-1)\tau(1-\tau)^{n'-2} \\ P_{T_c+\sigma'} &= 1-P_{\sigma'}-P_{T_s+\sigma'} = 1-(1-\tau)^{n'-1}-(n'-1)\tau(1-\tau)^{n'-2} \end{aligned} \tag{28}$$

$\bar{\sigma}$ can be expressed as follow:

$$\bar{\sigma} = \sigma' P_{\sigma'} + (T_s+\sigma')P_{T_s+\sigma'} + (T_c+\sigma')P_{T_c+\sigma'} \tag{29}$$

where T_s is the time cost for a successful transmission, and T_c is the average time the channel is sensed busy by each station during a collision. Let $H = PHY_{hdr} + MAC_{hdr}$ be the packet header, and δ be the propagation delay. T_s and T_c equal to

$$\begin{aligned} T_s &= DIFS + RTS + CTS + H + E[P] + ACK + 3SIFS + 4\delta \\ T_c &= DIFS + RTS + CTS + SIFS + \delta \end{aligned} \tag{30}$$

Based on analysis above, the value of q and $P_{t\_success}$ should be obtained before all the state steady probabilities of a node can be got. Firstly, the relation between them can be expressed based on equation (20) and (22).

$$q = e^{-\lambda' E[S_b]} = e^{-\lambda'\left(E[T_{Wait^1}]+E[T_{backoff}]\right)} \tag{31}$$

In addition, the relation between q and $P_{t\_success}$ also can be obtained by using the normalization condition.

$$\begin{aligned} &\sum_{i=0}^{m}\sum_{k=0}^{w_i-1}P_{i,k} + P_{Wait^1} + P_{Idle} + \sum_{i=0}^{m}\sum_{k=1}^{w_i-1}P_{Wait^2_{i,k}} + \sum_{i=0}^{m}P_{Wait^3_{i,0}} = 1 \\ &\left(1+\frac{\sigma}{T}\right)\frac{\beta-\alpha}{2}P_{0,0} + \frac{9h-1}{12h}P_{0,0} + \frac{q}{1-e^{-\lambda\sigma}}P_{0,0} + \frac{\alpha T_s}{T}P_{0,0} = 1 \\ &P_{0,0}\left(\left(1+\frac{\sigma}{T}\right)\frac{\beta-\alpha}{2} + \frac{9h-1}{12h} + \frac{q}{1-e^{-\lambda\sigma}} + \frac{\alpha T_s}{T}\right) = 1 \end{aligned} \tag{32}$$

The equation can be expressed as follow:

$$P_{0,0} = \frac{1}{\left(1+\frac{\sigma}{T}\right)\frac{\beta-\alpha}{2} + \frac{9h-1}{12h} + \frac{q}{1-e^{-\lambda\sigma}} + \frac{\alpha T_s}{T}} \tag{33}$$

The equation (31) and (33) are nonlinear and nonconvex. The equation set can be solved using arithmetic solution. And then, all the probabilities of $P_{i,k}$, P_{C_i}, P_{Idle}, P_{Wait^1}, $P_{Wait^2_{i,k}}$ and $P_{Wait^3_{i,0}}$ can be got too.

4. Performance analysis of CQM protocol

The metrics, such as throughput, average packet transmission delay are basic and important parameters of MAC protocol. Based on the analysis above, with the channel number, the node number, the packet rate and channel slot length taken into account, this section will analyze the metrics of CQM protocol.

4.1 Throughput analysis

Now, we will analyze the throughput of CQM protocol. Let S denotes the throughput of CQM system. In this paper, we assume the total of h channels are available, and each of them has the same bandwidth. Hence, the throughput of CQM protocol can be expressed as follow:

$$S = \sum_{i=1}^{h} \bar{S} = h\frac{E[l]}{E[slot]} \tag{34}$$

where $E[l]$ denotes the average payload size per virtual slot in one selected channel. $E[l]$ can be expressed as follow:

$$E[l] = P_n^1 l = C_{n'}^1 \tau (1-\tau)^{n'-1} l = n'\tau(1-\tau)^{n'-1} l \tag{35}$$

And $E[slot]$ denotes the virtual slot duration. It contains the duration of an empty slot time σ, the time duration T_S due to a successful transmission, and the time duration T_C due to a collision, respectively. And then the average slot duration $E[slot]$ can be obtained.

$$E[slot] = P_n^0\sigma + P_n^1 T_S + (1-P_n^0 - P_n^1)T_C \tag{36}$$

Finally, the normalized throughput of CQM protocol can be obtained.

$$\tilde{S} = \frac{S}{hC} = \frac{P_n^1 l}{\left(P_n^0\sigma + P_n^1 T_S + (1-P_n^0-P_n^1)T_C\right)C} \tag{37}$$

4.2 Average packet transmit delay analysis

In this section, we will analyze the average packet transmission delay at the MAC layer of CQM protocol. Our analysis considers the delay $E[D_{tr}]$ for a successfully transmitted packet in the case of saturation. $E[D_{tr}]$ is defined as the time from when a packet becomes eligible to be transmitted until it is transmitted successfully. So, $E[D_{tr}]$ is equal to the back off service time ($E[S_b]$) excluding the term corresponding to dropping a packet ($E[T_{drop}]$). Let $E[T_{drop}]$ denotes the average time from the packet leaves the MAC buffer until it reaches the retry limit. And then $E[T_{drop}]$ can be described as

$$E[T_{drop}] = T_{drop} P_{T_{drop}} \tag{38}$$

Where T_{drop} denotes the time from the packet leaves the MAC buffer until it reaches the retry limit. $P_{T_{drop}}$ denotes the probability of that a packet is dropped packet after it leaves the MAC buffer. According to the state steady probabilities analysis of a node in section 3, $E[T_{drop}]$ can be described as follow:

$$E[T_{drop}] = T_{drop} P_{T_{drop}} = \left(1 - P_{t\_success}\right)^{m+1} \left((m+1)(T_c + \gamma) + \bar{\sigma} \sum_{i=0}^{m} \frac{W_i - 1}{2} \right) \tag{39}$$

And then, the $E[D_{tr}]$ can be expressed as follow:

$$\begin{aligned} E[D_{tr}] &= E[S_b] - E[T_{drop}] \\ &= E[T_{Wait^1}] + E[T_{backoff}] - \left(1 - P_{t\_success}\right)^{m+1} \left((m+1)(T_c + \gamma) + \bar{\sigma} \sum_{i=0}^{m} \frac{W_i - 1}{2} \right) \end{aligned} \tag{40}$$

4.3 Numerical analysis of CQM protocol

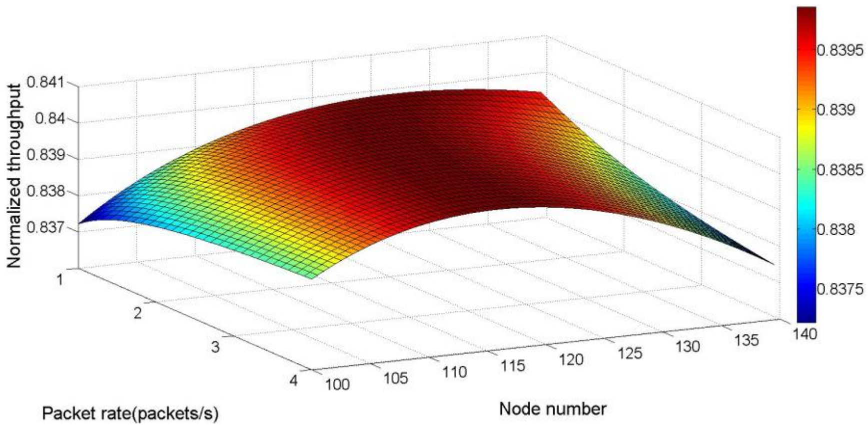
To show the influence of parameters (n , λ , T and h) to the performance ($E[D_{tr}]$ and S) of CQM system obviously, we now present the relationship between them by numerical analysis. A summary of parameters is shown in **Table 2**.

Table 2. CQM system parameters in numerical analysis

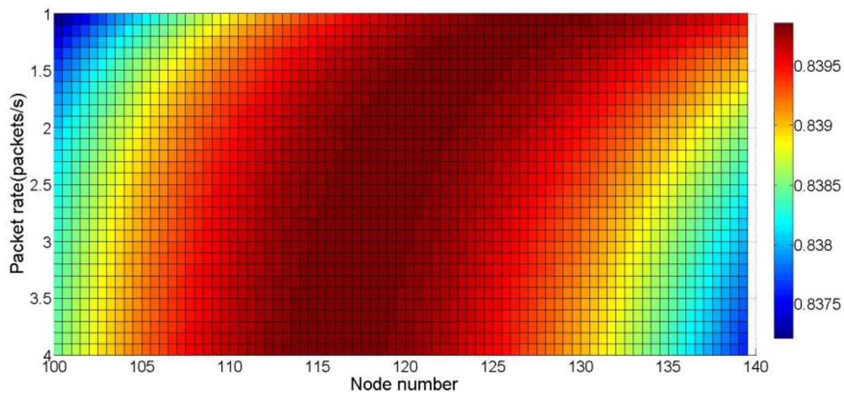
Packet length	8192 bits
MAC header	272 bits
Physical header(PHY)	128 bits
ACK	112 bits + PHY header
RTS	160bits + PHY header
CTS	112 bits + PHY header
SIFS	28 us
DIFS	128 us
m	6
m'	5
Slot duration	50 us
Propagation delay	1 us
Channel bit rate	1 Mbps
Channel number	3

The throughput versus node number and packet rate is shown in **Fig. 3**, when the channel slot length is set to 100ms.

As is shown in **Fig. 3**(a), in the beginning, the throughput increases gradually with the increase of node number in a certain packet rate. And then, it reaches its maximum value when the node number reaches one certain value. Finally, the normalized throughput decreases gradually. This is because that with the increase of node number and packet rate, more and more nodes transmit packet successfully in one channel slot. When the network size is small, the CQM system is in unsaturation situation. And there are few collisions during transmission, the collision probability is extremely small. Hence, the throughput of CQM system increases gradually with the increase of node number in the beginning. And then, the CQM system will turn into saturation situation, when the node number reach a certain value. In this situation, the number of node that is successfully transmitted in one channel slot reaches its maximum. Hence, the throughput of CQM protocol reaches its maximum value too. And finally, the CQM system will enter into oversaturation situation, if the node number continues to increase. In this situation, collision occurs frequently, the node that can transmit successfully in saturation situation is likely to collide with the other node. Hence, the throughput will decrease. As is similar to the impact of node number, the normalized throughput has the same change trend with the increased packet rate.



(a) Throughput of CQM system (3-D)



(b) Throughput of CQM system (Top view)

Fig. 3. Throughput versus node number and packet rate with $T = 100ms$

As is shown in **Fig. 3**(b), with the increase of node number and packet rate, the throughput increases gradually. When node number and packet rate reach a bound, the network will turn into saturation state, and throughput reaches its maximum value. In this paper, we call it saturation bound.

The impact of the number of channels on the performance of CQM performance is also shown in **Fig. 4**, with $\lambda = 2, T = 100ms$.

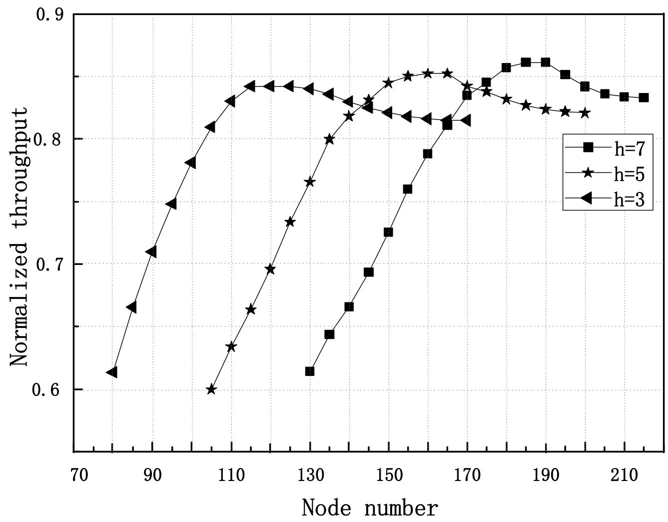


Fig. 4. Throughput versus node number with different channel number

As is shown in **Fig. 4**, the change trend of normalized throughput with the increase of node number is the same as that in **Fig. 3**. With different channel number, the normalized throughput increases with the increase of node number. And then, it reaches its maximum value when node number reaches one certain value. Finally, it decreases with the increase of node number gradually. In addition, with the increase of channel number, the normalized throughput in saturation case increases slowly. This is because that collision probability decreases with the increase of channel number. That is to say, the utilization rate of frequency increases with the increase of channel number.

Fig. 5 shows the relationship between throughput, node number and channel slot length. In this system, the channel number is set to 3, and the packet rate is set to 2 packets/s.

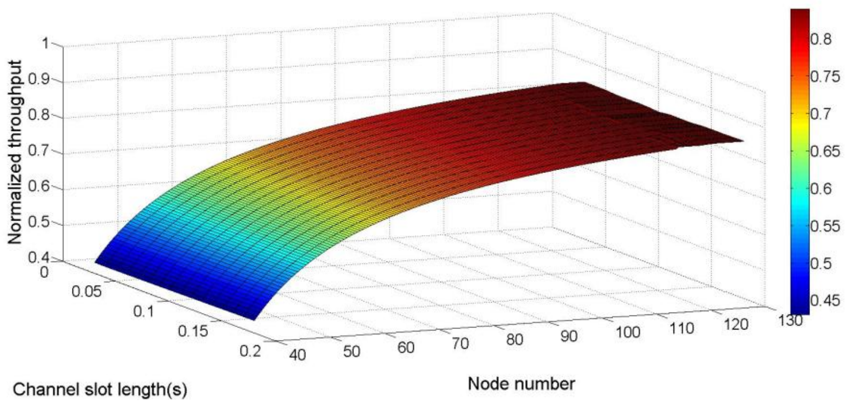
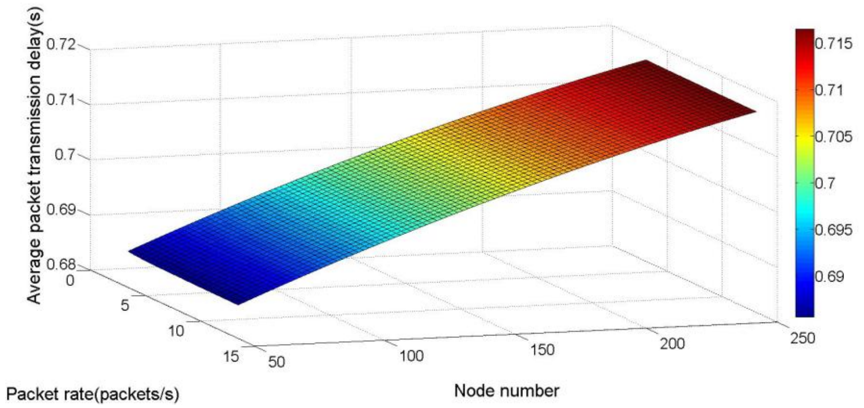


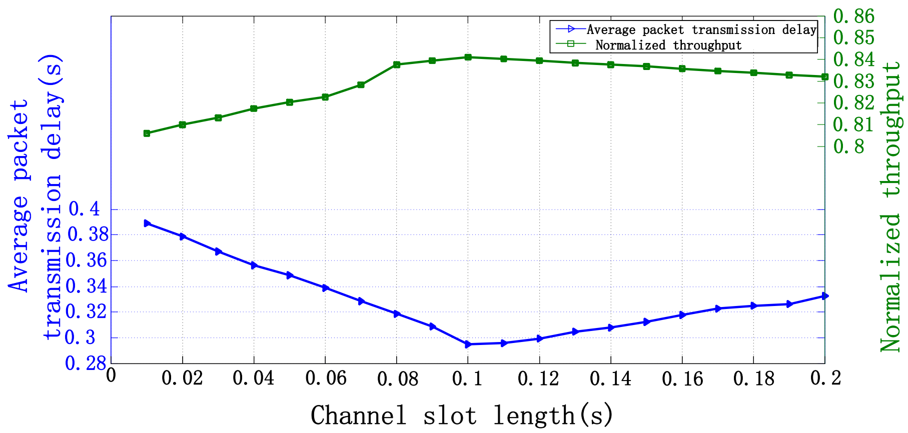
Fig. 5. Throughput versus node number and channel slot length with $\lambda = 2$

As is shown in **Fig. 5**, on one hand, the normalized throughput increases with the increase of node number in a certain channel slot length, and it approaches to its maximum value when the network is in saturation case. On the other hand, the throughput changes slowly with the increase of channel slot length(in the range of [0.03,0.18]) in a certain node number.

The relation between parameters (n, λ, T) and S can be revealed by numerical analysis above. The most maximum throughput can be obtained when parameters (n, λ, T) break through the saturation bound. And then, the change trend of average packet delay with the change of parameters (n, λ, T) can be shown in **Fig. 6** (a) and **Fig. 6** (b).



(a) Average packet transmission delay of CQM system with $T = 100ms$ (3-D)



(b) Average packet transmission delay of CQM system with $n = 36, \lambda = 8$

Fig. 6. Average packet transmission delay in oversaturation case

As is shown in **Fig. 6**(a), with a given $T = 100ms$, the average packet delay increases nonlinearly with the increase of node number in oversaturation case. The increased packet rate has little influence on the average packet delay. According to Eq. (40) above, the value of average packet transmission delay depends on the time cost in checking stage and back off stage. And the time cost in queuing stage is not the part of packet transmission delay. In oversaturation situation, the channel slot is almost utilized entirely. With the increase of node number, the time cost in back off stage will increase, owing to the increase of collision probability. Hence, the average packet transmission delay increases with the increase of node number, and the increase of packet rate has little influence on the average packet transmission delay in saturation situation. In addition, the packet dropping rate will increases sharply with the increase of packet rate in oversaturation case. **Fig. 6**(b) shows that with the given $\lambda = 8$ and $n = 36$, the maximum throughput and minimum average packet transmission delay can be obtained when channel slot length is set to 0.1s. That is to say, for a given λ and n, the network can reach the saturation situation only when the channel slot length reaches one certain value.

Based on the analysis above, for a network with a certain channel slot length, the maximum throughput, minimum average packet delay and minimum drop rate can be obtained only in the saturation bound case. And we will find the saturation bound of CQM system based on bird swarm algorithm in section 5.

5. Bird swarm algorithm based saturation bound

In this section, we will find the saturation bound of CQM system. According to analysis above, the best performance of CQM system can be obtained when the network is in saturation bound case. In this way, the problem can be considered to be a optimization problem. The goal is to find pairs of value of n and λ in saturation bound case with a certain T.

For this optimization problem, to get the less average packet transmission delay and less drop rate under the situation with the most maximum throughput, we set the objective function as follow:

$$F = 1000\tilde{S} + E[D_{tr}] + \lambda \tag{41}$$

And the constraint conditions are as follow:

$$\begin{aligned} & n \in Z; \lambda > 0 \\ & 0 < P_{t\_success} \le 1; 0 < q \le 1; \end{aligned} \tag{42}$$

According to equation (37) and (38), this optimization problem is nonlinear and nonconvex. To attack this optimization problem, bird swarm algorithm (BSA) is adopted.

BSA has elegant properties of effectiveness, superiority and stability to solve nonlinear and nonconvex problem, proposed by Xian-bing Meng in 2015[23]. It is based on the three kinds of behaviors of bird: foraging behavior, vigilance behavior and flight behavior. The BSA concludes four search strategies associated with five simplified rules.

a. Foraging behavior

Each bird searches for food according to its experience and the swarms' experience. This behavior can be expressed as follows:

$$x_{i,j}^{t+1} = x_{i,j}^{t} + \left(p_{i,j} - x_{i,j}^{t}\right) \times Cog \times rand\left(0,1\right) + \left(g_j - x_{i,j}^{t}\right) \times Soc \times rand\left(0,1\right) \tag{43}$$

where $x_{i,j}^{t}$ denotes the position of the ith bird at time step t. $rand(0,1)$ denotes independent uniformly distributed numbers in (0,1). Cog and Soc are two positive numbers, which can be respectively called as cognitive and social accelerated coefficients. $p_{i,j}$ denotes the best previous position of the ith bird and g_i denotes the best previous position shared by the swarm.

b. Vigilance behavior

Birds would try to move to the centre of swarm, and they would inevitably compete with each other. Thus, each bird would not directly move towards the centre of the swarm. These motions can be formulated as follows:

$$
\begin{gathered}
x_{i,j}^{t+1} = x_{i,j}^{t} + A1\left(mean_j - x_{i,j}^{t}\right)\times rand(0,1) + A2\left(p_{k,j} - x_{i,j}^{t}\right)\times rand(-1,1) \\
A1 = a1\times \exp\left(-\frac{pFit_i}{sumFit+\varepsilon}\times N\right) \\
A2 = a2\times \exp\left(\left(\frac{pFit_i - pFit_k}{\left|pFit_k - pFit_i\right|+\varepsilon}\right)\frac{pFit_i\times N}{sumFit+\varepsilon}\right)
\end{gathered}
\tag{44}
$$

where k is a positive integer, which is randomly chosen between 1 and N. $a1$ and $a2$ are two positive constants in [0,2]. $pFit_i$ denotes the ith bird's best fitness value and $sumFit$ represents the sum of the swarms' best fitness value. $mean_j$ denotes the jth element of the average position of the whole swarm. And ε is the smallest constant in the computer.

c. Flight behavior

Birds may fly to another site in response to predation threat, foraging or any other reasons. When arrived at a new site, they would forage for food again. Some birds acting as producers would search for food patches, while others try to feed from the food patch found by the producers. The producers and scroungers can be separated from the swarm. The behaviors of the producers and scroungers can be described mathematically as follows, respectively:

$$
x_{i,j}^{t+1} = x_{i,j}^{t} + randn(0,1)\times x_{i,j}^{t},\quad x_{i,j}^{t+1} = x_{i,j}^{t} + \left(x_{k,j}^{t} - x_{i,j}^{t}\right)\times FL\times rand(0,1)
\tag{45}
$$

where $randn(0,1)$ denotes Gaussian distributed random number with mean 0 and standard deviation 1. FL means that the scrounger would follow the producer to search for food.

The processing of BSA algorithm can be shown in **Fig. 7**.

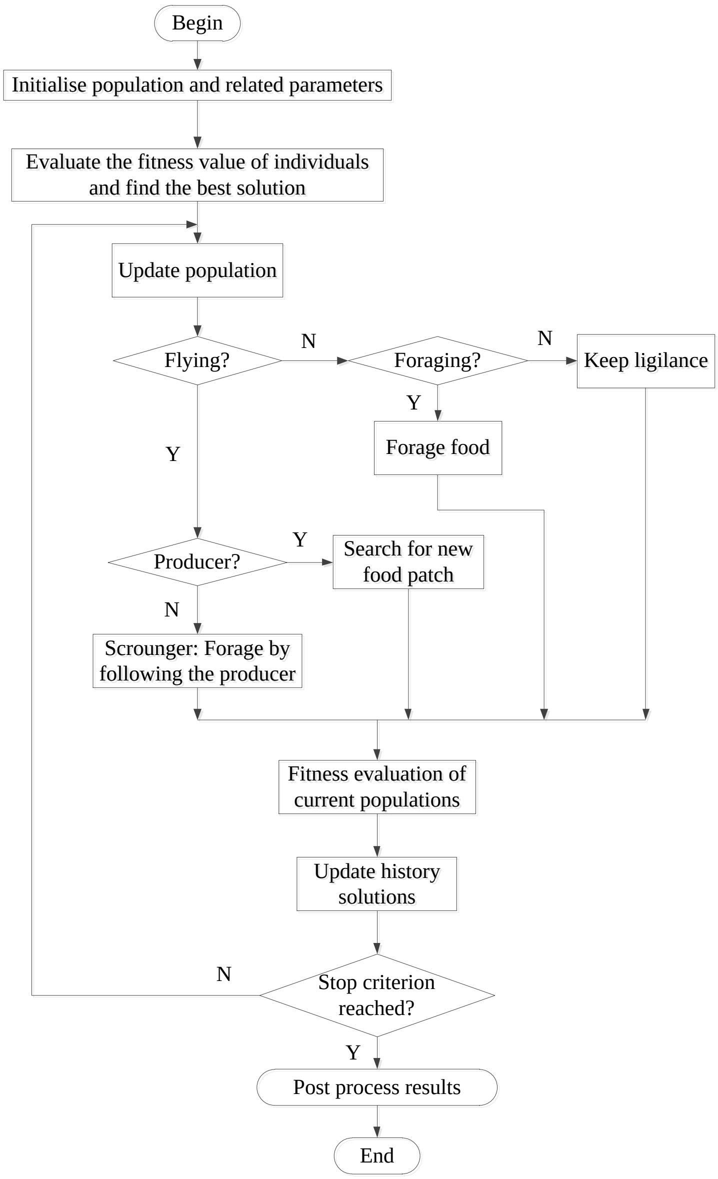


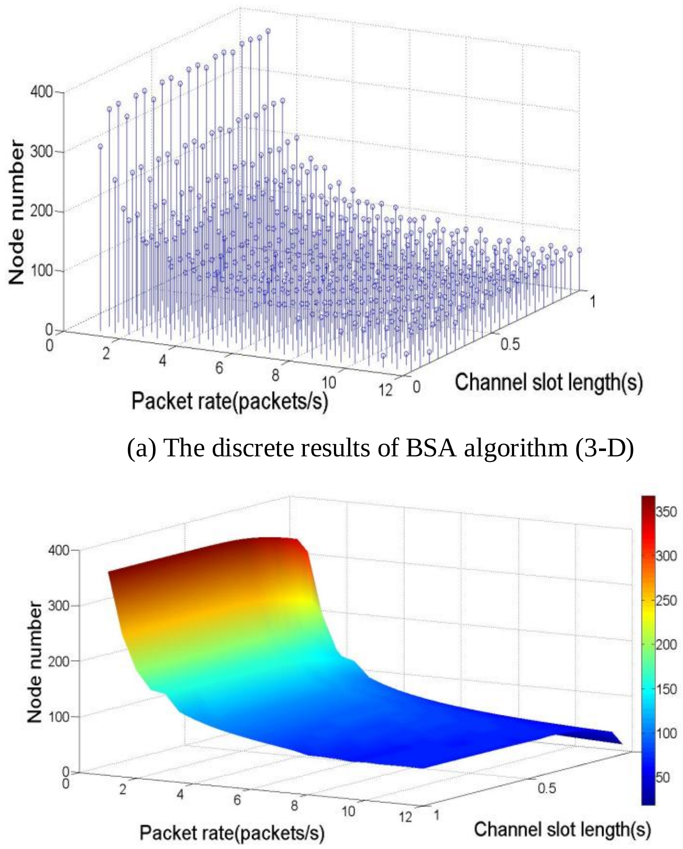
Fig. 7. The processing of BSA algorithm

Based on BSA algorithm, for a certain channel slot length T, we can get the tuple(n, λ) at the saturation bound. The parameter values of BSA algorithm in this section are given in **Table 3**.

Table 3. The parameter values of the BSA algorithm

Parameters	C	S	a1	a2	FL	FQ	T	N
Values	1.5	1.5	1	1	$FL \in [0.5, 0.9]$	3	50	100

In this section, the channel slot length T is selected in range of [0.01,1]. And **Fig. 8**(a) shows the results of BSA algorithm with 3 channels. **Fig. 8**(b) is the smooth result of **Fig. 8**(a).



(a) The discrete results of BSA algorithm (3-D)

(b) The smooth results of BSA algorithm (3-D)

Fig. 8. The saturation bound results obtained by BSA algorithm

The points in **Fig. 8**(a) denote the results of saturation bound condition obtained by BSA algorithm. One point in **Fig. 8**(a) corresponding to one possible tuple (n, λ, T), with which the CQM system can enter into saturation case. The surface in **Fig. 8**(b) can denote the saturation bound of CQM system obviously. As is shown in **Fig. 8**(b), with a given channel slot, the value of packet rate changes with that of node number.

When T is set to 100ms, the relationship between node number and packet rate for different channel number in the saturation bound case can be illustrated in **Fig. 9**.

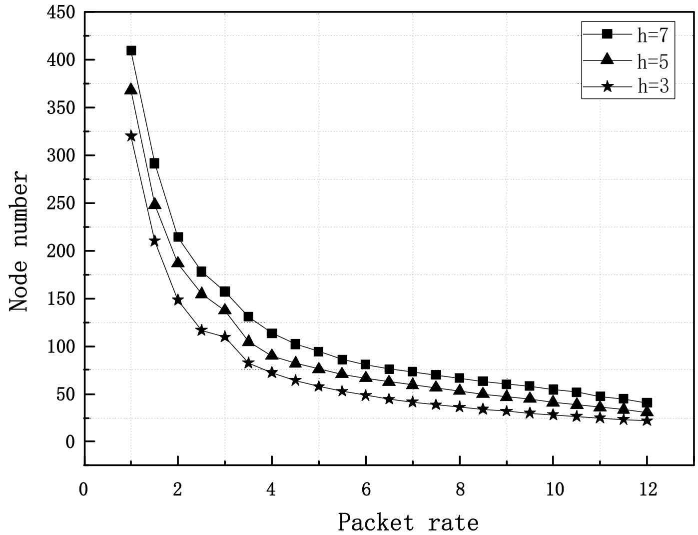


Fig. 9. The saturation bound of CQM system with different channel number

As is shown in **Fig. 9**, in saturation bound case, the node number decreases with the increase of packet rate with $T=100ms$ for different channel number. And with a given packet rate, the node number increases with the increase of channel number. That is to say, only when the node number and packet rate reach a certain condition, the channel slot can be utilized fully, and the frequency utilization ratio of CQM system can reach its maximum value.

To verify the saturation bouds of different channel number with $\lambda=8$, **Fig. 10** shows the performance comparison of CQM system with different channel number in unstauration case and saturation case.

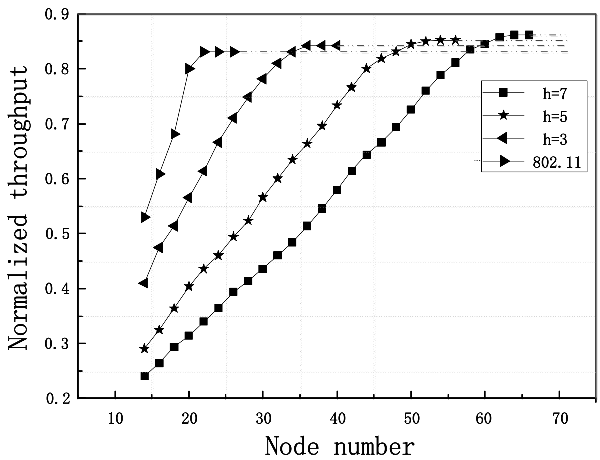


Fig. 10. The normalized throughput versus node number with $T=100ms$ and different channel number

As is shown in **Fig. 10**, for network with different channel number, the normalized throughput increases with the increase of node number in unsaturation case, and can approaches to its maximum value in saturation case. In this scenario, when the node numbers reach 40, 60, 68 respectively, the CQM system can enter into saturation case, which can match well with the result in **Fig .8**. The saturation bound of CQM protocol can be verified in this scenario. In addition, compared with 802.11 DCF with single channel, the maximum normalized throughputs of multi-channel system increase, owing to the high frequency utilization ratio and low collision probability. And the multichannel system can accommodate more nodes in saturation case. That is to say, in high diversity node situation, the multichannel system can perform better than the single system.

6. Performance evaluation

To verify our Markov model and theoretical analysis of CQM protocol, we compared theoretical analysis results with simulation results obtained by Qualnet simulator. Qualnet simulator is the only parallel and message level network simulation tool, developed by Scalable Networks Technologies. It has the faster running speed, higher accuracy and better extensibility, and is suitable for development and simulation of Ad hoc network and wireless sensor networks.

In our simulations, nodes are uniformly placed in an area of 170 m × 170 m. The transmission range of a node is 250 m. In this way, all nodes can stay in the transmission range of others. A node keeps a separate FIFO queue for each of its neighbors. Each node may act as a sender where the destination is chosen from its one-hop neighbors. The packet rate is selected in [2,8]. And the channel slot is set to 100ms. To get the performance of different channel number, every node is equipped with several interfaces. The interface can be assumed to be different channels, and the CQM channel hopping strategy is used in our simulations. The number of interface is set to 3, 5, 7. The system parameters are same as the numerical analysis in section 4.

Firstly, we present the aggregate throughput between the CQM and McMAC protocols in single-hop networks as shown in **Fig. 11**. For McMAC, $P_{deviate}$ denotes the probability of changing schedule to follow the intended receiver's channel-hopping sequence. In this simulation, the $P_{deviate}$ is set to 0.1. Each traffic flow in the network uses the constant bit rate (CBR) traffic model, and the packet size is 1024 bytes, and the packet rate is set to 8.

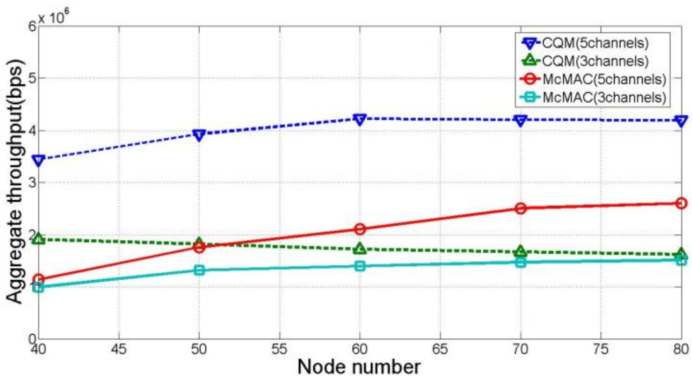


Fig. 11. The aggregate throughput comparison between CQM and McMAC protocols

As is shown in **Fig. 11**, CQM performs better than McMAC obviously due to eliminating the missing receiver problem. In addition, in 3 channels scenario, the aggregate throughput of CQM system decreases with the increase of node number. This is because that the CQM system is in oversaturation case. In 5 channels scenario, the CQM system enters into saturation case when the value of node number reaches 60.

And then, we will verify the saturation bound of numerical analysis results. **Fig. 12** shows results comparison between numerical analysis and simulation when λ is set to 2, 3, 4, 5, 6, 7, 8.

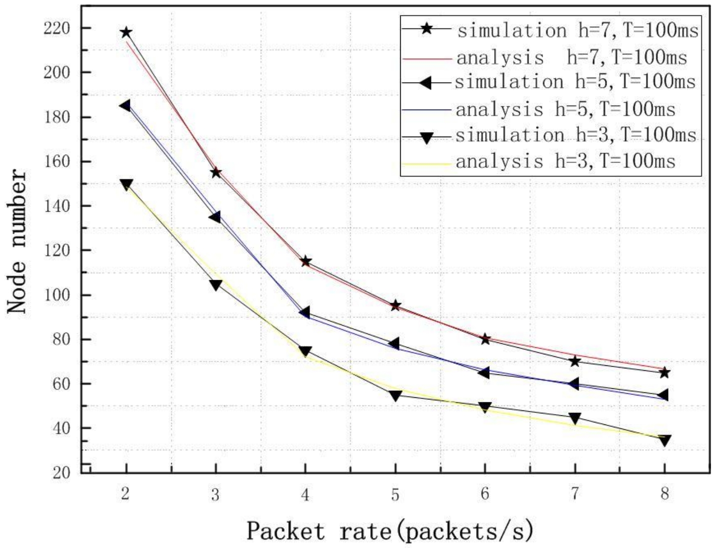


Fig. 12. The comparison between analysis results and simulation results with different channel number

As is shown in **Fig. 12**, the simulation results can match well with the numerical analysis results. In addition, the more nodes can be accommodated with the increase of channel number. It also can be verified that the multichannel system can perform better than the single system in high diversity node situation.

When given a saturation bound situation as shown in **Fig. 12**, we can get the average normalized throughputs and packet transmission delay by simulating 7 situations respectively when h is set to 3, 5 and 7, as shown in **Fig. 13**.

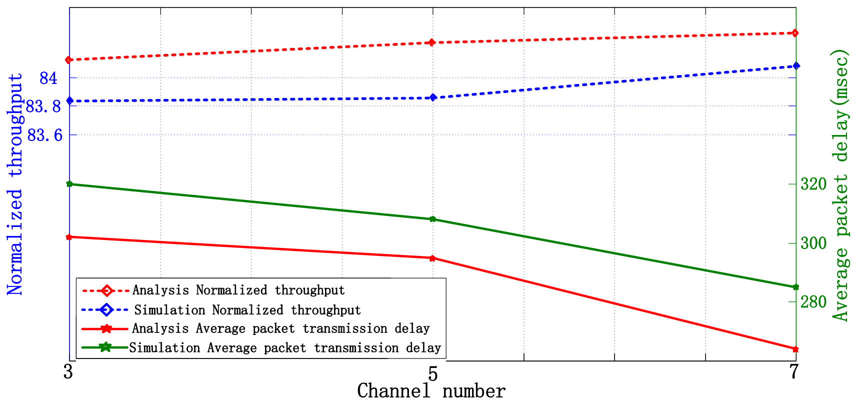


Fig. 13. The average performance comparison between analysis results and simulation results with different channel number

As is shown in **Fig. 13**, the average normalized throughput and packet transmission delay obtained by simulations can match well with the numerical analysis. The Markov model and theoretical analysis of CQM protocol can be verified too.

7. Conclusions

In high diversity node situation, multichannel MAC protocol can help to sharing the traffic loads among different channels. Hence, the collisions single-channel MAC protocols suffered from can be alleviated, and the frequency utilization rate can be improved. Among multichannel MAC protocols, the CQM protocol performed better for its high efficiency and easy to be realized.

In this paper, to obtain the most optimal performance of CQM protocol, an analytical model is proposed for CQM protocol. And then, we analyze the throughput and average packet transmission delay of CQM system, considering the related parameters (node number n, packet rate λ, channel slot length T and channel number h). The saturation bound situation is found by numerical analysis. Combined with the optimization theory, the saturation bound is obtained by BSA algorithm. The Markov chain model and saturation bound are verified by simulating on Qualnet platform. The results show that the simulation results and analytical results match very well.

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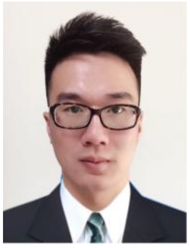

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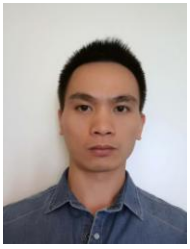

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