國立交通大學

資訊科學與工程研究所

碩 士 論 文

感知雲端網路實現控制頻道之研究

The Study of Control Channel Realization in Cognitive Radio Cloud Networks

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The Study of Control Channel Realization in Cognitive Radio Cloud Networks

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摘要

在感知無線電網絡（CRN）中，CR 用戶可以通過頻譜感知來使用頻帶以增加頻帶利用率，但同時要避免干擾授權用戶的使用。因此關鍵是精確的頻譜感測與有效地避免干擾。在我們的設計中，雲端會維護頻譜資料庫，以供 CR AP 查詢頻帶的可用性。此外，CR AP 會負責協調 CR 用戶的資料傳輸。為了實現這兩個目標，所考慮的是 CRN 必須有一個控制頻道以供 CR AP 與所管理的 CR 用戶來交換所需的控制訊息。但是 TVB 的可用性會隨時間動態地改變，因此在 CRN 中使用 TVB 來當作控制頻帶是不可行的。由於上述原因，我們提出了一種新的設計，透過 IEEE 802.11 PCF 模式來達成 CR 控制通道的實現。在 PCF 期間，CR AP 可以收集感測裝置的感測資料，收集 CR 用戶的資源配置請求，以及通知資源分配結果。通過正確的設置 DCF 和 PCF 模式的週期，我們可以即時的更新頻譜資料庫，增加 TVB 的頻道利用率。然而，這種設計的主要挑戰是如何保證 PCF 的週期性。在這篇論文中，我們提出了兩種機制來解決這一設計問題。另一方面，雖然更長的 PCF 週期時間會顯著改善頻譜資料庫的準確性與 TVB 利用率，但也減少 DCF 的週期時間並降低傳統 WiFi 用戶的效能。為了研究這個問題的權衡，我們探討此異質網絡，並分別推導出用於收集感測回報與資源請求的適當時間。此外，探討在給定 WiFi 用戶數和效能降低門檻，我們可以服務多少 CR 用戶。並且通過簡單的 TVB 頻譜配置演算法和考慮頻譜估測準確度，來探討 TVB 系統的效能。

Abstract

In cognitive radio networks (CRN), CR users can use the available channels through spectrum sensing to increase the bandwidth utilization while avoiding the interference to licensed users at the same time. Accurate spectrum sensing is critical to effectively avoid interference. In our design, there is a spectrum database maintained in the Cloud for CR Access Points (AP) to query channel availability. Besides, CR APs are responsible to coordinate data transmissions of CR users. To achieve these two goals, the considered CRN must have a control channel for the CR AP and managed CR users to exchange required control messages. The availability of TV Band channels may dynamically change, it is not feasible to utilize a TVB channel as the control channel of the CRN. Due to the above described reason, we propose a novel design of CR control channel implementation by enabling the PCF mode of IEEE 802.11. In a PCF period, a CR AP is able to collect sensing reports sent by sensing devices, collect resource requests sent by CR users, as well as announcing the resource allocation results. Through proper setting the cycle of DCF and PCF modes, we can update the spectrum database in time and increase the TVB channel utilization. However, the major challenge of this design is how to guarantee the periodicity of PCF cycle. In this thesis, we propose two mechanisms to tackle this design issue. On the other hand, though a longer PCF cycle time will significantly improve the accuracy of the spectrum database and the TVB utilization, it also decreases the DCF cycle time, as well as the throughput performance of legacy WiFi users. To investigate this tradeoff, we model this heterogeneous network, derive the proper time slots for sensing report collection and resource requests, respectively. Besides, we investigate that, upon given he number of active WiFi users and throughput degradation threshold, how many CR users can be served. Furthermore, by integrating a simple TVB channel scheduling algorithm and taking the sensing accuracy into consideration, we study the throughput performance of the TVB system.

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1. Introduction

1.1Background

Cognitive Radio Network

In recent years, more and more mobile device have wireless communication capability, for example iphone and ipad. For the service type of user, the requirement of traditional voice service is transformed to the requirement of multimedia service. In such environment transforming, the demand on bandwidth increases year by year, and even appear the condition that the scarcity of spectrum resource. According to FCC (Federal Communications Commission) survey result, the average utilization of licensed band doesn’t reach 70%.In order to increase the licensed band utilization, the concept of cognitive radio is proposed at 1998. Therefore, in order to solve the scarcity of spectrum resource problem, we have to not only increase the transmission efficiency but also increase the spectrum utilization.

Compared to traditional wireless communication technology, cognitive radio uses the opportunity channel access scheme on the licensed channel to improve the licensed channel utilization. Therefore, in cognitive radio network, we define two kinds of users, the licensed band user which we call primary user (PU) and the unlicensed band user which we call secondary user (SU). The concept of cognitive radio that can solve the scarcity of spectrum resource is that secondary user can use the primary user’s channel when he sense the channel is not used by the primary user. For guarantee primary user’s authority, the secondary user should vacate the channel immediately when primary user wants to use channel. Moreover, FCC has defined the standard of cognitive radio on using the TV White Space. After this movement, other organizations start to define the cognitive radio communication protocol ,for example, 802.22, ECMA392, 802, 11ah, 802.11af, and 802.11m … .

Although the basic idea of cognitive radio is simple, cognitive radio imposes the new challenges that don’t exist in the conventional wireless networks. The time-varying channel availability causes the design problem for Medium Access Control (MAC) layer. One of the design problems is how the secondary users decide when and which channel that they should hop to it and send/receive their data without affecting the primary user. In order not to affecting the primary user, the secondary user should have the ability to sense, to measure, and evaluate the channel availabilities. Unfortunately, the behavior of primary user is unknown and unpredictable to secondary users, but the major task of cognitive radio network is spectrum sensing and spectrum map construction. Beside the spectrum sensing problem, the other problem is spectrum accessing of secondary users that how and how long the secondary users use the channel when the channel is idle, and vacate the occupied channel to primary users as quick as possible.

In order to improve spectrum utilization and system throughput, we focus on the study of control channel realization of cognitive radio MAC design in this paper.

802.11 Network

In order to let any kind of communication device can connect to each other, IEEE 802.11 group defines the standard for 802.11 PHY layer and MAC layer. After defining the standard, IEEE 802.11 group also defines 802.11a and 802.11e for supplement QOS and security to increase system throughput. In the following section, we would focus on introduction the 802.11b MAC architecture and protocol.

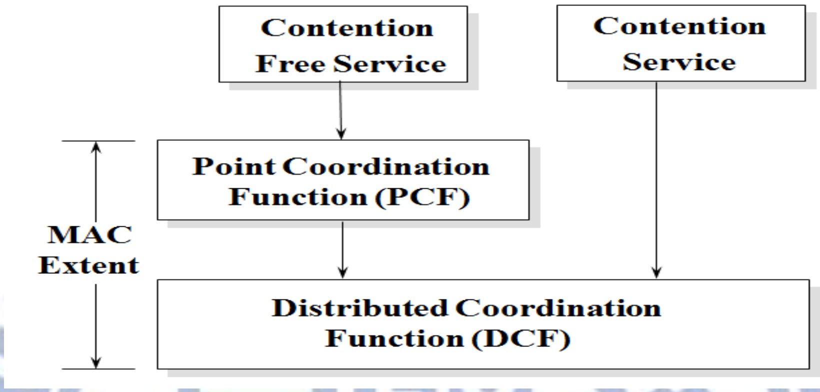

Fig1. MAC Service mode in the 802.11 network

In the 802.11 network, the service is divided into two modes: (1) The one is contention service that we notate Distributed Coordination Function (DCF). In DCF mode, 802.11 users adopt CSMA/CA and random BACKOFF scheme to content the wireless channels.

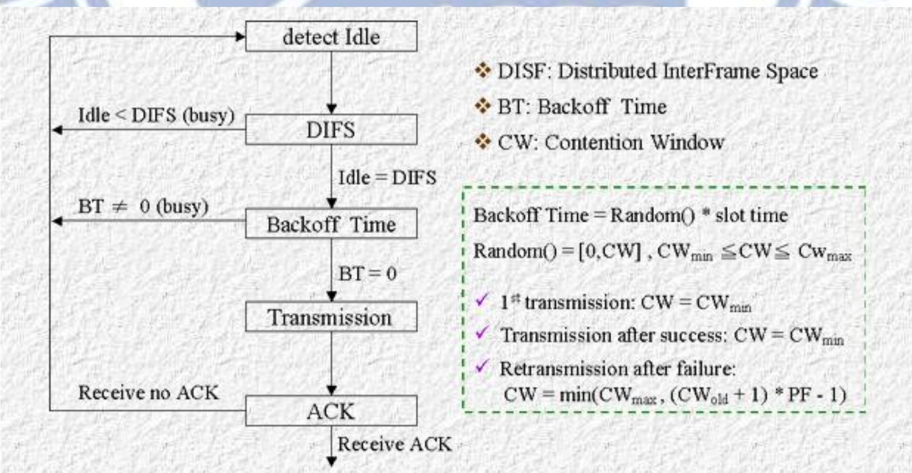

Fig2. CSMA/CS and BACKOFF scheme

(2)The other one is contention free service that we notate Point Coordination Function (PCF). In PCF mode, there exists an Access Point (AP) to coordinate the network, and user transmits his data when he is polled by AP.

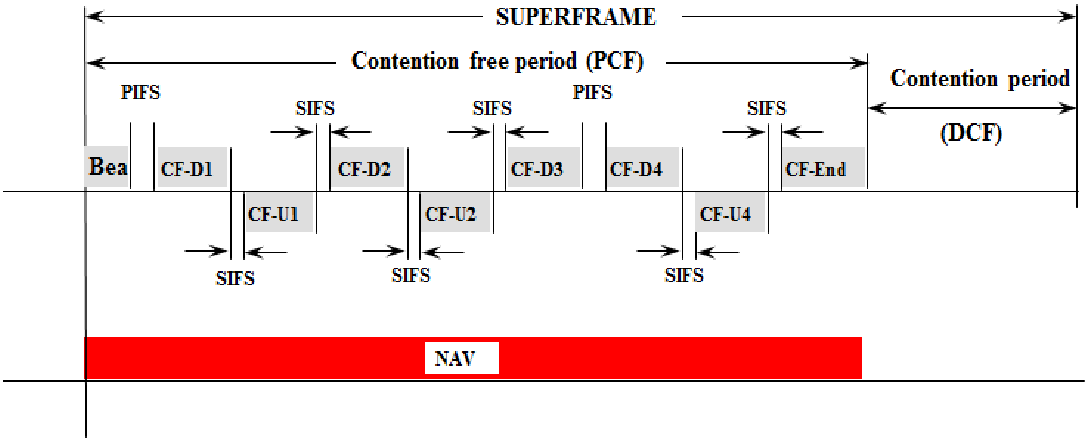

Fig3. The SUPERFRAME of 802.11 network

The SUPERFRAME of 802.11 network is composed of one DCF duration and one PCF duration. The duration of a SUPERFRAME is not identical, and the PCF's duration and the DCF's duration are not identical in different SUPERFRAME because of the reason that when the AP wants to initial the PCF, he also needs to content the channel with a high channel access priority PIFS. Therefore, if the channel is occupied by any user, the PCF mode would delay until the channel is idle. Then, it also impact the duration of SUPERFRAME.

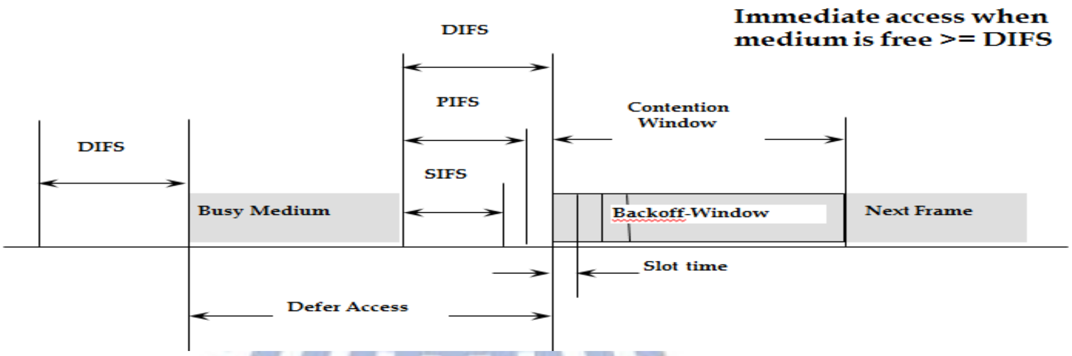

Fig4. Channel Access Priority for WIFI network

CR Mac Protocol

FCC has defined a series of standard for guarantee the primary user's authority. As an example as IEEE 802.22, cognitive radio system has to use the spectrum sensing report and the location of secondary user to construct the primary user Spectrum Landscape for guaranteeing the signal of secondary user would not affect the signal of primary user. In order to avoid the signal interference to primary user, CR MAC protocol has to sense the channel periodically and accurately.

Then, there exist two approaches in CR Mac Protocol: (1) The one is single rendezvous that assume existing a common control channel for secondary users to communicate. When there exist a CC, we can activity coordinate the spectrum sensing policy and the data channel assignment quickly. Base on the concept increasing channel utilization, we can quickly exchange information through CC, and then transmit data on the corresponding data channel. But this assumption is strong for time-varying channel in cognitive radio network. With fixed CC in TVWS, it might cause long time channel blocking by primary user or channel saturation by lots of secondary users. Moreover, the time to find a new CC in TVWS is a strong influence in system throughput calculation.

(2)The other one is parallel rendezvous that is without the common control and uses channel hopping sequence to communicate between sender and receiver. In the parallel rendezvous, secondary user also should possess spectrum sensing ability and guarantee that SU would not affect the licensed band user signal quantity. Because there doesn't exist a common control channel (CC), SUs should rendezvous on some channel to exchange the necessary control message before SUs start to transmit their data. After SUs exchange the necessary control message, sender and receiver will hop to the corresponding channel until SUs confirm this channel is idle to transmit their data according to the hopping sequence scheme. But in the cognitive radio network which user uses opportunity channel access scheme, there would not always exist a channel that is idle for a long time, so we can't guarantee the rendezvous time on some channel is enough for SUs to complete the data transmission, and we might need many rendezvouses to guarantee data transmission be completed. Another problem in the parallel rendezvous is that when the number of user in the same region increases, the requirement of data transmission also increases. In such condition, there would cause an amount of transmit pair hopping to the same channel, even transmit data at the same time, cause collision, and then decrease the system throughput.

1.2 Motivation and Objective

Follow the FCC standard, we have to construct the spectrum database and guarantee the interference level for PU. Time-varying channels can't guarantee the spectrum sensing report interval can be consistent and the SU sensing report can't be received accurately by the coordinator. Therefore, how to find and construct an always available CC for spectrum sensing would be the major task in CR network.

Many papers don't consider the control channel problem or the time that coordinator spends on finding an available channel for constructing the control channel might be long with the time-varying channels. Therefore, we use the ISM band to construct as the control channel for coordinating the secondary users. Future, we can coordinate the secondary users through the control channel immediately.

We try to use 802.11 PCF mode in ISM band for Control Channel realization in Cognitive Radio Network. We use the ISM band to design control channel so we want to decrease the impact of 802.11 users as possible as we can. For cognitive radio network, guarantee the spectrum sensing report, sensing report interval, and increase the data channel utilization.

2. Related Work

In cognitive radio network, Media Access Control Protocols is significant, and there exist two approaches in CR MAC protocol: (1) single rendezvous (2) parallel rendezvous. The difference about the two approaches is that there exists a control channel (CC) as a rendezvous channel in single rendezvous, and all the secondary users can exchange control message and parameter information on the CC. Parallel rendezvous is without CC and bases on channel hopping sequence and then follow the hopping sequence to switch on different channels. We want CC realization for secondary to exchange information, so we would focus on the research of single rendezvous MAC protocol.

In [3], the author proposes a Hardware-Constraint Cognitive MAC (HC-MAC) method which assumes a specialized CC for secondary users exchanging RTS/CTS message, and derives the optimal stopping problem that bases on the sensing overhead and transmission constrain. Further, the author derives the relationship between sensing time and throughput for secondary users reaching the optimal transmission efficiency. But the defect of HC-MAC is only one transmission pair can transmit data. It means that when anyone secondary user hears C-RTS message of C-CTS message, the secondary user would stop to transmit data, and then it would decrease the system throughput and channel utilization. Beside the secondary users can exchange control information on the CC, [4] divide the time duration into many beacon intervals, and there are three subdivisions in the beacon interval: channel selection, sensing, and data transmission. In channel selection period, secondary users would send Ad Hoc Traffic Indication Message (ATIM) message to announce the receiver that the data channel he selects. If the receiver successfully receives the message, he would transmit an ATIM-ACK message to the sender. In the sensing period, one unlicensed transmission pair would sense the channel and broadcast in the channel selection period to determine the channel is available or not. In the data transmission period, the author uses RTS/CTS/DATA/ACK four way handshake method to solve the collision problem just like the collision avoidance method in IEEE 802.11 CSMA/CA protocol. The advantage in this paper is that secondary users can transmit data on data channel (DC) or control channel (CC) for avoiding the condition that all the DCs are occupied by primary users. But, the disadvantage is all secondary users have to synchronization, so there should exist one user to broadcast the beacon. On the other hand, it is too many overhead in the channel selection period for control information exchanging. Although this situation can be solved by stretching the duration of channel selection period, but it would decrease the system throughput.

[5] propose Opportunistic Spectrum MAC (OS-MAC) protocol that the author uses the concept of Secondary User Group (SUG) to represent a communication group which any member wants to communication with other member in this group, and only one user can transmit data at the same time in the same group. Beside, time is divided into some Opportunistic Spectrum Period (QSP), and QSP is composed of three phases: select phase, delegate phase, and update phase. In OS-MAC protocol, every data channel has a Delegate Secondary User (DSU), and the DSU is assigned by all the secondary users that want to transmit data on this data channel. The DSU acquires channels information periodically on the CC, and every SUG selects the best channel to transmit data. However, the author assumes the part how secondary users form SUG is well knew by all secondary users. Further, DSU wouldn’t coordinate with other SUGs for efficient spectrum sensing, so it means every SUG is independent and doesn’t adopt the silent period scheme. This paper doesn’t consider the primary user protection problem.

[6] propose a cross-layer based opportunistic multi-channel MAC protocol in the ad-hoc network. The protocol assumes every secondary user has two transceivers, one is used on the CC, and other one is used on the DC. The author proposes two spectrum sensing scheme, Random Sensing Policy (RSP) and Negotiation-based Sensing Policy (NSP). In RSP, every secondary user randomly selects one channel and senses it. Because we adopt randomly selection scheme, more and more channels can be sensed when the number of secondary user increases. But the disadvantage is the repeating sensing problem. In NSP, secondary users would know the channel set that is sensing by other secondary users, and sense one of the remaining channels. But the disadvantage is the communication overhead.

[7], consider the control channel realization into the SUPERFRAME architecture, but would need a lot of information exchange. It would cause the control overhead. [8], exist a CC for secondary user to exchange control message, but there arises single

control channel saturation problem and long –time blocking problem for this CC. [9], [10] divide the secondary users into some groups according to different region, and the secondary users in the same group would have same available channel set. The users in the same group would have a high probability to find a channel as the CC, and users need to coordinate a new CC when the original CC is occupied by some primary user. After the network topology changing, we should separate the group again for ensuring the available channel set is same in the same group.

[11] adopt the scheme as the RTS/CTS in 802.11 for secondary users to content channels. In every twice spectrum sensing period, secondary users can send RTS message to AP for acquiring available channel. If the AP correctly receives the RTS message, the AP would send CTS to the correspondent secondary user, and the secondary user acquires this channel during data transmission period. [12] adopt a De-centralized Hybrid MAC protocol (DDH-MAC) that secondary users would sense the ISM band for finding the CC. If there is no CC on the ISM band, users would select a PCCH and some BCCH for updating user's Free Available List (FLA), and users use PCCH and RTS/CTS scheme to exchange control message and transmit data with other users.

For standard 802.11ah [16], the main application of IEEE 802.11ah is sensor network. The measure information should be delivered to a fusion center like an AP. Among 3C (Capacity, Cost, Coverage), Cost and Coverage are more significant than Capacity for this application. To extend coverage with low complexity and low power, the proposed a permuted OFDM symbol repetition scheme under the framework of IEEE 802.11a/g OFDM. But the standard focus on channel selection and 802.11 MAC coexistence in 900MHz.

According to above references, the design issue of CR MAC protocol can be divided into three phases: (1) Find Common Control Channel. There doesn't always an idle channel existence, so the problem is how we find a suitable channel. (2) Sensing Period. The sensing scheme and sensing duration would affect the channel utilization, so the problem is how to find a suitable sensing mechanism. (3) Data Transmission Period (or Rendezvous Period). When secondary users transmit their packets on the data channels, the resource scheduling function not only consider the throughput but also consider the risk function for affecting primary user's authority.

3. System Model

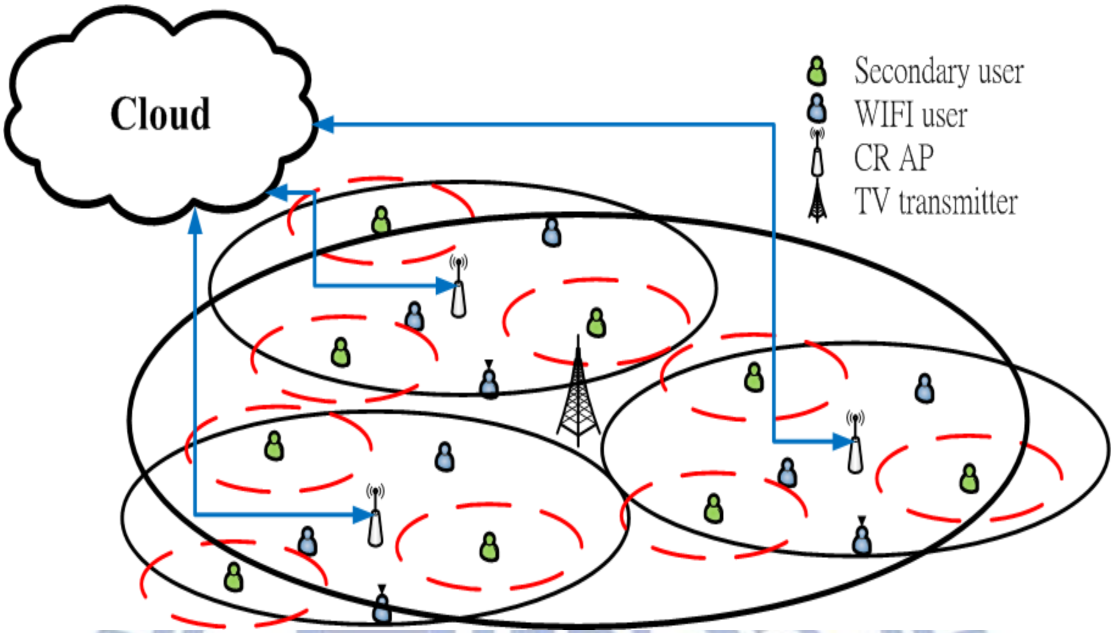

Fig5. Cognitive Radio Cloud Network architecture

In the system model, we base on the reference [15] that the author proposes that the rapid growth of Cloud computing and fiber-to-the-home (FTTH) internet services, one can start to imagine a future wireless city where seamless CR services provided by access points (APs) and Cloud computing. With such a CR Cloud Networking (CRCN) service, the public can get seamless and free baseline wireless access to the internet.

In the CRCN architecture, there exist some TV transmitters and some WIFI networks, and the coverage of TV transmitter covers number of WIFI network. Some WIFI users and secondary users coexist in the heterogeneous network, and access points (APs) act the coordinator to control the WIFI network and CR network. APs can collect the spectrum sensing result which we adopt cooperative spectrum sensing scheme by user position and sensing ability of secondary users. Beside these devices, there is a cloud can acquire the sensing results from APs periodically, and the cloud can provide APs the available channel set through the spectrum evaluation algorithm and channel assignment scheme. Consequently, we adopt the infrastructure-hierarchical cognitive radio cloud network architecture to control the channel access and user management

Function

- AP acts the coordinator for both 802.11 users and SUs through the ISM band in the CRCN architecture.
- Every SU has two antennas for the CC and the DC. Every SU could hop to the corresponding channel and sense it according to AP's beacon.
- Every SU can send a resource request to the AP through the CC. AP can decide the channel assignment to the SUs.
- We divide the SUs to some SU's groups according to the requirement of cooperative spectrum sensing by the Cloud.

Assumption

- AP divides the SUs to some SU's groups same as the sensing listing according to the SU's position and the preciseness of sensing information from cloud.
- Cloud can evaluate and management the spectrum situation through the sensing report and we can acquire the available channel set from cloud periodically.
- For coexistence with 802.11 network, we define two new frame formats , CR parameter set and CR request , for AP and SUs to communication with each other.
- AP, 802.11 users, and SUs are time synchronous.

4. Proposed Method

We use the ISM band as our control channel (CC), TVWS as our data channel (DC), and there are one CC and number of DCs in our network. Based 802.11 MAC architecture, one SUPERFRAME is composed of one PCF mode and one DCF mode, and this architecture is also adopted in the proposed CR MAC architecture on CC. Then, we use the PCF mode to design our CR MAC, and WIFI users transmit their packets on the DCF mode by using CSMA/CS protocol just same as the normal infrastructure WIFI network.

4.1 CR MAC Architecture

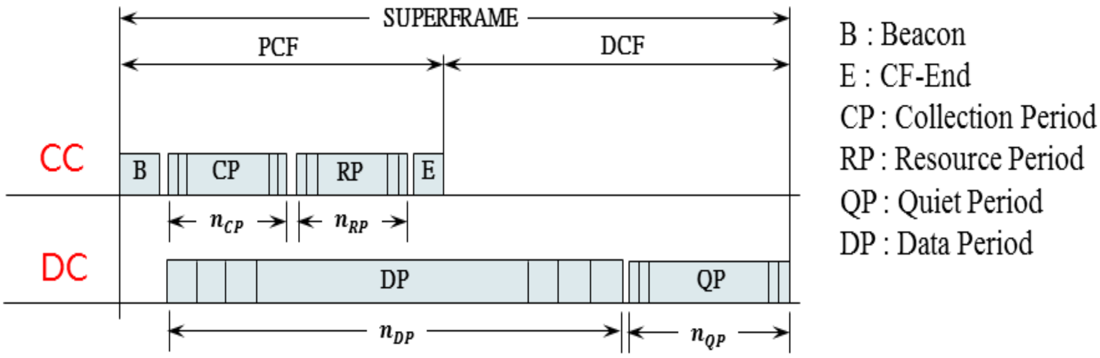

Fig6. CR MAC Architecture

In this section, we firstly introduce how we use the PCF mode to design CC of our CR MAC. For achieving activity coordination on spectrum sensing and channel assignment, spectrum management, and increase channel utilization, we divide the PCF duration into three parts: (1) Control Period (2) Collection Period (3) Resource Period. In the control period, it includes BEACON and CFP_END period. BEACON is used by AP to announce SUs the scheduling result and polling listing, and also announce WIFI users to initial PCF mode. CFP_END is used by AP to announce both SUs and WIFI users the ending time of PCF mode. Future, in the collection period, it is designed for AP to collect SU’s sensing result by sequential polling. Finally, Resource Period is designed for SUs to send resource request for acquire available channels.

In the DC of our CR MAC, we divide into two parts: (1) Data Period (2) Quiet Period. First, Quiet Period is designed for SUs to sense the DC and SUs can’t send any data in the period. Then, Data Period is designed for data transmission of SUs and divided into uplink and downlink. Collection Period, Resource Period, Data Period, and Quiet Period are all divided into slots. The duration of slot in different period is according the respective requirement.

4.2 Frame Format Definition

In this section, for the coexistence of cognitive radio network, we base the characteristic that includes spectrum sensing, sensing report, resource request, and channel assignment to define three frame formats: Association Request, Resource Request, and CR Parameter Set.

4.2.1 Association Request

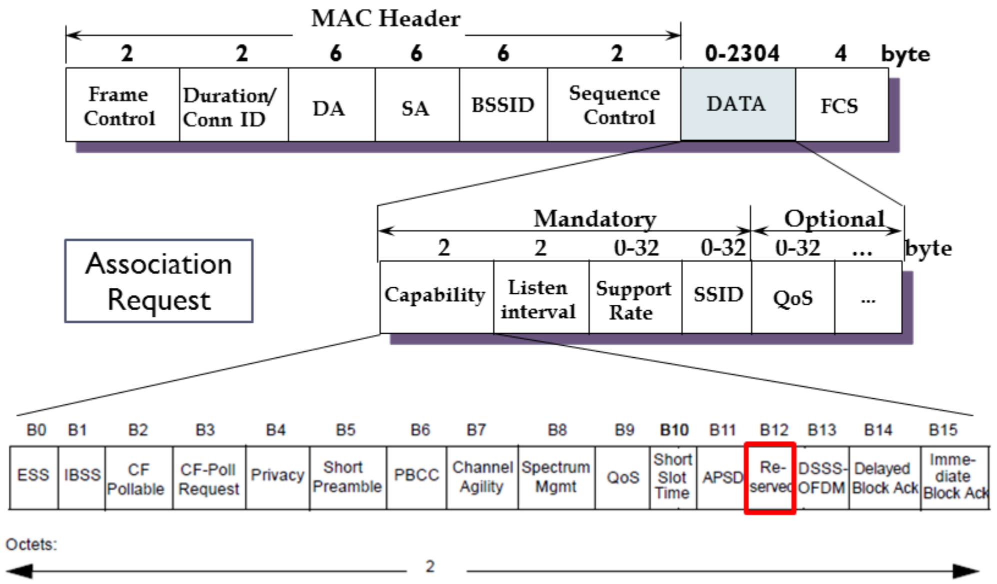

Fig7. Frame Format – Association Request

For identifying SUs and WIFI users, we revise the reserved field in the capability information of 802.11 association request and denote CR-Pollable. CR-Pollable of 1 indicates the user is a SU, and CR-Pollable of 0 indicates the user is a WIFI user.

4.2.2 Resource Request

For SU's sensing report and resource request, we define the new frame format and denote Resource Request.

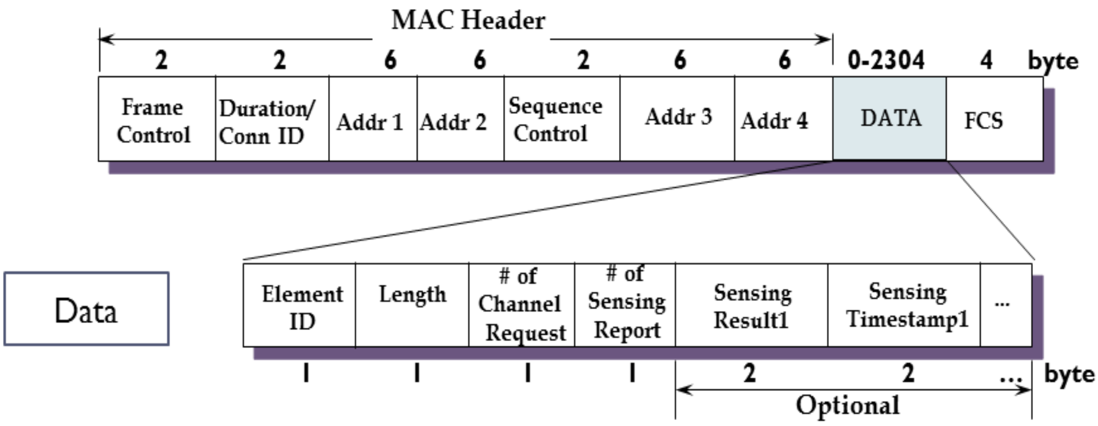

Fig8. Frame Format – Resource Request

# of Channel Request

# of Channel Request indicates the resource request of the user. If user needs to report sensing result, it also guarantees its resource request can be exactly received by the AP.

# of Sensing report

# of Sensing report indicates the total channels that are sensed by the user. Channel count of 0 indicates that is a channel request without sensing result.

Sensing Result

Sensing Result indicates which data channel is sensed by the user and the channel condition of this data channel.

Sensing Timestamp

Sensing Timestamp indicates the time that the SU sense the data channel

4.2.3 CR Parameter Set

For spectrum sensing and channel assignment coordination, we define the new frame format and denote CR Parameter Set.

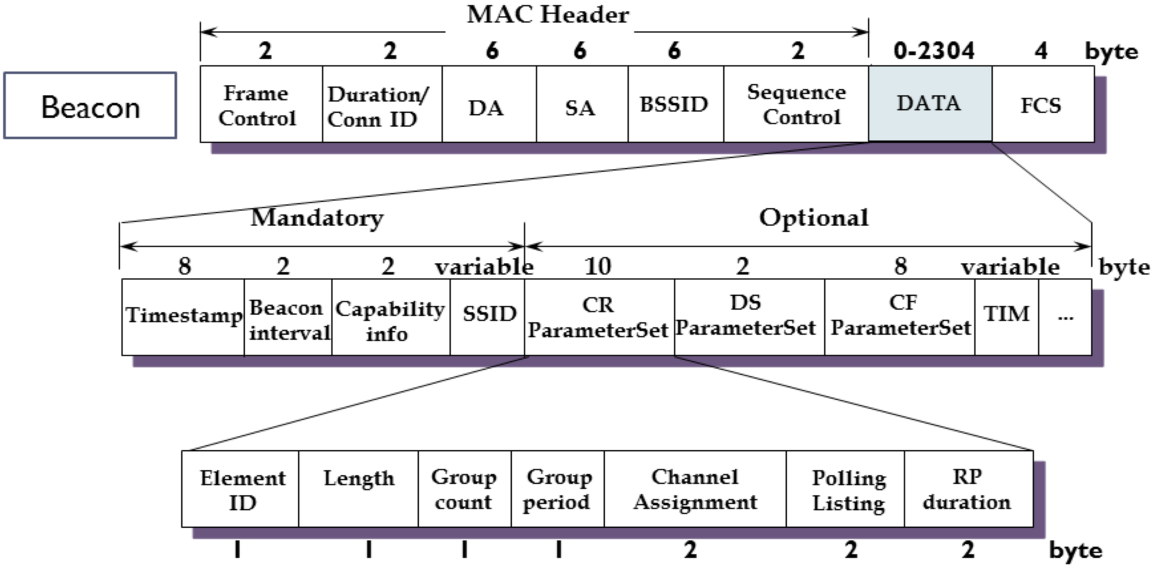

Fig9. Frame Format – CR Parameter Set

Group count

Group count indicates the SU's group id in the polling listing

Group period

Group period indicates the number of SU's group

Channel Assignment

Channel Assignment indicates the channel assignment for SUs transmission.

Polling Listing

Polling Listing indicates that the number of SUs and which SUs would be polled in this SUPERFRAME.

RP (Resource Period) duration

Resource Period duration indicates the time that SU can send associated request and resource request to the AP.

4.3 PCF Access Delay

Notation:

- T'_{DCF}: residual DCF duration
- *M*: the number of WIFI users
- *r*: saturation user transmission probability
- $t_{backoff}$: the average back-off time
- t_{data}: the average data frame transmission time
- t_{ack}: the ACK frame transmission time
- t_{SIFS}: the duration of SIFS
- t_{DIFS}: the duration of DIFS
- t_{PIFS}: the duration of PIFS
- t_{EIFS}: the duration of EIFS
- *D*: the expect PCF access delay
- δ_a: the threshold of PCF access delay

When AP wants to broadcast the beacon for initialing the PCF mode, it maybe cause access delay because of that users use CSMA/CA scheme in DCF mode. That, it means the channel would be occupied by user at the moment.

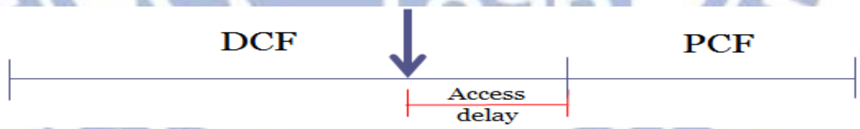

Fig10. PCF Access Delay problem

It would cause the PCF mode delay, and also delay the time for AP to boardcast contorl message that include spectrume sensing listing and channel assignment. Moreover, causing the sensing report delay would impact spectrum database update and then cause the spectrum evluation result. Therefore, we want to analysis the access delay and eliminate it. We assume every WIFI user are saturation(always have data to transmit), and we consider the condition at the moment of initial PCF mode:

Case1 : AP doesn't have data to transmit : $1 - r$

$$d1 = t_{backoff} + (1-r)^{M-1} * t_{PIFS} + (1-(1-r)^{M-1}) * \left(\frac{t_{data}+t_{SIFS}+t_{ACK}}{2} + t_{PIFS}\right)$$

The moment is in the previous backoff period, and AP waits till the backoff period finish. Then, If no user transmits data , AP waits for PIFS, and then start to broadcast beacon. If someone transmits data, the AP wait for data transmission time and PIFS, and then also start to broadcast beacon.

Case2 : AP has data to transmit : r

$$d_2 = (1-r)^{M-1} * \left(\frac{t_{DIFS}+t_{backoff}+t_{data}+t_{SIFS}+t_{ACK}}{2} + t_{PIFS}\right) +$$

$$(1-(1-r)^{M-1}) * \left(\frac{t_{DIFS}+t_{backoff}+t_{data}+t_{EIFS}}{2} + t_{PIFS}\right)$$

The time is not in the previous backoff period, and AP needs to transmit the data. AP might successfully transmit data or cause collision. Then, the AP wait for PIFS and then broadcast beacon.

Then, the PCF Access Delay can be wirtten as below:

$$D = (1-r) \cdot d1 + r \cdot d2$$

4.3.2 Interval Consistency Method

For solve the PCF access delay problem, we base the analysis access delay D, and propose the AP-aware modification.

AP-aware modification

If the AP discovers that the residual time plus an extra short time cannot accommodate a data frame with a predefined probability p_0, i.e,

$$p(t_{DIFS}+t_{backoff}+t_{data}+t_{SIFS}+t_{ACK} \leq T'_{DCF}+\delta_a) \leq p_0$$

CR-AP sends a beacon at time $T'_{DCF} - t_{PIFS}$

RTS/CTS modification

If AP or MS wants to transmit data in DCF mode:

AP

$$t_{DIFS}+t_{backoff}+t_{data}+t_{SIFS}+t_{ack} \leq T'_{DCF}+\delta$$

MS

send the RTS message to the AP, and the AP check the duration of this data transmission :

$$NAV_{RTS} \leq T'_{DCF}+\delta$$

Successful : AP send the CTS message to the user

Failed : AP ignore the RTS message

4.4 SU Coexistence problem

Notation:

- σ: the slot time , δ: the propagation delay
- p_{tr}: the probability that at least one user transmits his data
- p_M: the probability that only one WIFI user transmits his data
- p_k: the probability that only one SU transmits his data
- M: the number of WIFI users in the WIFI network
- K: the number of SUs in the WIFI network
- r: user transmission probability
- L_{as}: the size of associated packet
- Ts: the transmit time of data packet
- Tas: the transmit time of associated packet
- Tc: the collision time caused by users data transmission at the same time
- H: PHY header + MAC header

We firstly introduce the user authenticated/associated procedure in the WIFI network. The user state may be one of following three states:

(1) unauthenticated/unassociated

(2) authenticated/unassociated

(3) authenticated/associated

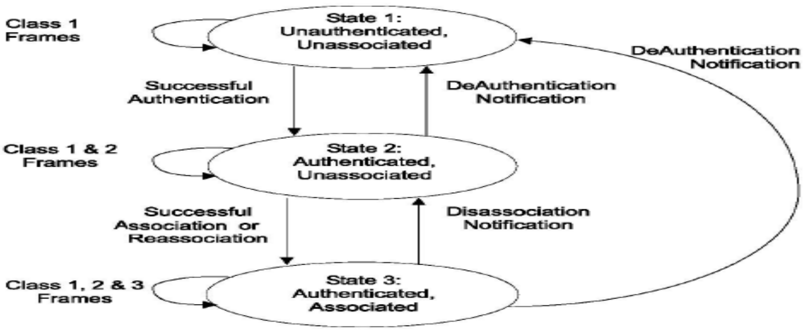

Figure 11-6—Relationship between state variables and services

Fig11. The service state in the WIFI network

In state (1), user should use the DCF mode to send the authentication request to AP for acquiring the necessary security information till AP successfully receives the authentication request and send the authentication response to the user. After user successfully receives the authentication response from AP, he can go to the state (2).

Then, in state (2), user should use the DCF mode to send the association request to AP for verifying user capability till AP successfully receives the association request and send the association response to the user. After user successfully receives the associated response from AP, he can go to the state (3). In state (3), user can send data frame in the DCF mode.

For support mobility, 802.11 standard has proposed that users can resend the association request to AP to maintain user state. Follow this procedure, we assume SUs would resend association request in the DCF mode again before timeout to support mobility. For a stable system, if we want K SUs be stable (always successfully send his association request before timeout) in the network, we should calculate the relationship between arrival rate and service rate of SUs. Finally, we can calculate the maximum number of SUs that can coexistence in the heterogeneous network, and it is a stable network.

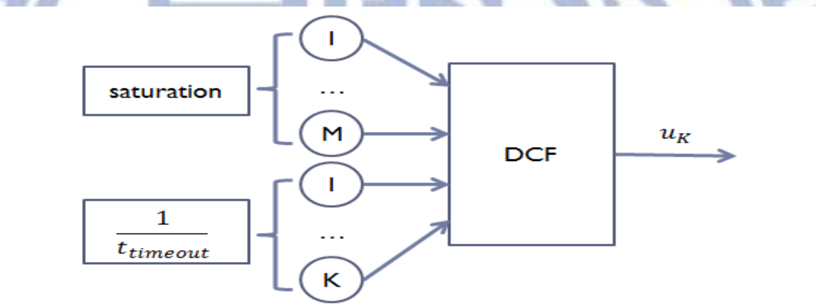

Fig12.SU association Model

We assume that M WIFI users are saturation (always have data to transmit) and K SUs are all the state3 users and would back to DCF to send association request before timeout. Then, with the number of SU, WIFI user in the DCF mode, and user transmission probability, we can calculate the service rate for SUs that success association request to maintain user state. The data access scheme of WIFI user would impact the service rate of SUs, so we firstly derivate channel access time for Basic Access and RTS/CTS Access:

Basic Access

- T_s = DIFS+δ+H+E[P]+SIFS+δ+ACK
- T_{as} = DIFS+δ+L_{as}+SIFS+δ+ACK
- T_c = DIFS+δ+$\frac{M(\text{H+E[P]})+KL_{as}}{M+K}$+EIFS

RTS/CTS Access

- T_s = DIFS+δ+RTS+SIFS+δ+CTS+SIFS+δ+H+E[P]+SIFS+δ+ACK
- T_{as} = DIFS+δ+RTS+SIFS+δ+CTS+SIFS+δ+L_{as}+SIFS+δ+ACK
- T_c = DIFS+δ+RTS+EIFS

The arrival rate of SUs:

- $\lambda_K = \frac{K}{t_{timeout}}$

The service rate of SUs:

- $p_{tr} = 1 - (1-r)^{M+K}$
- $p_M = \frac{Mr(1-r)^{M+K-1}}{p_{tr}} = \frac{Mr(1-r)^{M+K-1}}{1-(1-r)^{M+K}}$
- $p_K = \frac{kr(1-r)^{M+K-1}}{p_{tr}} = \frac{kr(1-r)^{M+K-1}}{1-(1-r)^{M+K}}$
- $u_K = \frac{p_{tr}p_K}{(1-p_{tr})\sigma + p_{tr}p_M T_s + p_{tr}p_K T_{as} + p_{tr}(1-p_M-p_K)\,T_c}$

Then, the relationship between arrival rate and service rate in a stable network is:

$$\lambda_K \leq \mu_K$$

When the arrival rate is equal to service rate, we can find the maximum number of SUs coexistence in the network.

4.5 PCF duration

Notation:

- T: the duration of SUPERFRAME
- T_{PCF}: the duration of PCF mode
- T_{DCF}: the duration of DCF mode
- r_b: Basic Rate
- r_t: Transmit Rate
- t_P: the transmit time of Preamble
- t_{PHY}: the transmit time of Physical Header
- t_{beacon}: the tansmit time of Beacon frame
- t_{CF_END}: the tansmit time of CF_END frame
- $t_{request}$: the time for user to send a resource request
- t_{report}: the time for user to transmit an sensing data
- t_{poll}: the time for AP to transmit an polling command
- t_{CP}: the duration of Collection Period
- t_{RP}: the duration of Resource Period
- t_{QP}: the duration of Quiet Period
- t_{DP}: the duration of Data Period
- L_{beacon}: the packet size of Beacon frame
- L_{CF_END}: the packet size of CF_END frame
- $L_{request}$: the packet size of resource request frame
- L_{report}: the packet size of sensing frame
- L_{poll}: the packet size of polling frame
- N : the number of data channels
- K : the number of secondary users
- k : the number of polling secondary users
- α : the one channel sample sensing time for SU
- δ_s : the accuracy threshold of spectrum evaluation algorithm

- n_d: the number of available TVB channels
- *m* : the number of require sensing samples per data channel
- *s* : the probability of report error
- n_{RP}: the number of slots in the RP duration
- *R(x , K) :* The expect acquired request when we divide the time duration into *x* slots and *K* users adopt the random selection scheme

In our CR MAC architecture, we use the PCF mode to implementation the MAC architecture and we would discuss the duration in this section. Then, it is composed of four parts: Beacon, Collection Period, Resource Period, and CF_END. The duration of PCF mode can be written as below:

$$T_{PCF} = t_{beacon} + t_{CP} + t_{RP} + t_{CF\_end}$$

1) Beacon and CF_END

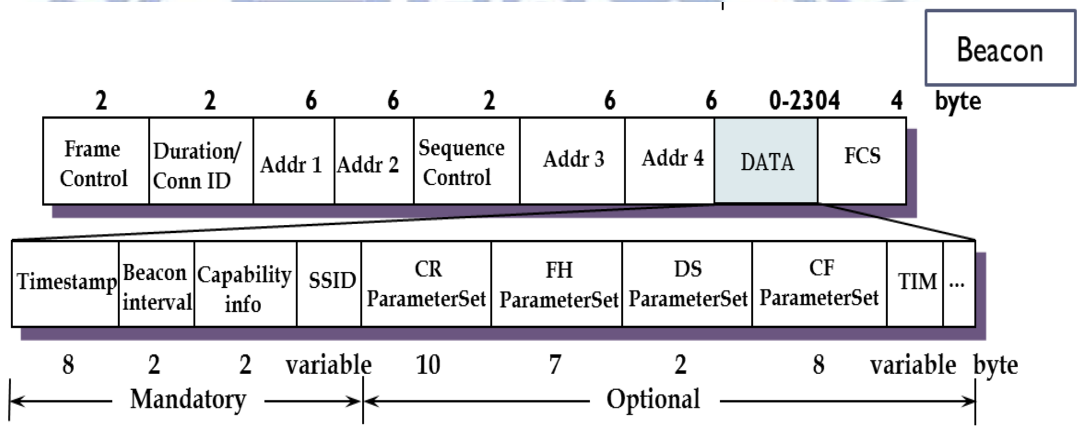

Fig13. Beacon Frame Format

$$t_{beacon} = t_P + t_{PHY} + \frac{L_{beacon}}{r_b}$$

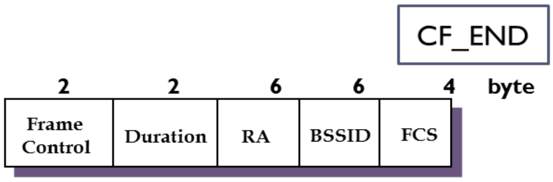

Fig14. CF_END frame Format

$$t_{CF\_end} = t_P + t_{PHY} + \frac{L_{CF\_end}}{r_b}$$

2) Collection Period

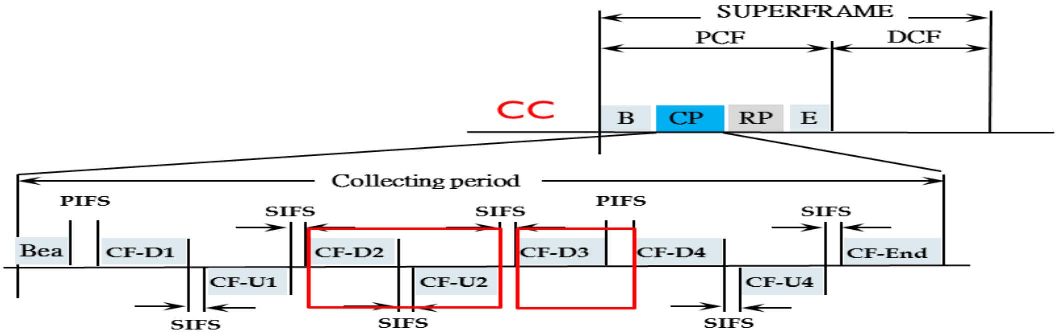

Fig15. The procedure in Collection Period

$$t_{report} = t_P + t_{PHY} + \frac{L_{report}}{r_t}$$

$$t_{poll} = t_P + t_{PHY} + \frac{L_{poll}}{r_b}$$

AP polls k SUs in this collection period, and $m \leq k \cdot s \leq$ K. If AP successfully poll one SU, the poll time would include the poll time, SIFS time, and sensing report time. If report error occurs, AP waits for PIFS and continues to poll the next SU. Then, the CP duration can be written as below:

$$t_{CP} = k \cdot [(1-s) \cdot (t_{poll} + 2 \cdot t_{SIFS} + t_{report}) + s \cdot (t_{poll} + t_{PIFS})]$$

3) Resource Period

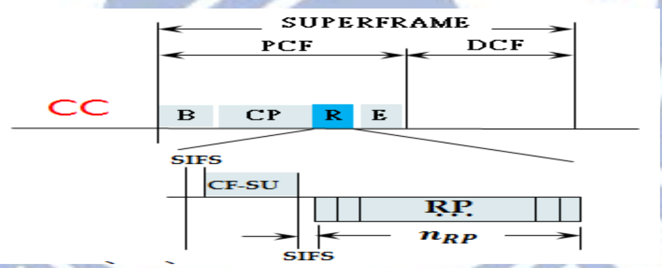

Fig16. The procedure of Resource Period

$$t_{request} = t_P + t_{PHY} + \frac{L_{request}}{r_b}$$

For increasing the channel utilization, we have to guarantee the number of acquire resource requests exceed the number of available channels. The duration of RP can be written as below:

$$t_{RP} = t_{poll} + n_{RP} \cdot t_{request} + 2 \cdot t_{SIFS}$$

$$n_{RP} = argmin\, R(x, K) \geq n_d$$

4) Quiet Period

According to the number of sensing sample for achieving the sensing accuracy, one channel sensing time, and the number of sensing users, we could write the duration of QP as below:

$$t_{QP} = \alpha \left\lceil \frac{Nm}{k} \right\rceil$$

5) Data Period

Then, the DP duration is according to the beacon transmission time and QP duration, and the duration of DP is written as below:

$$t_{DP} = T - (t_{beacon} + t_{QP})$$

Future, we could calculate the CR network throughput through the QP duration and the acquire request from the RP.

4.6 Random Selection Scheme

In this section, we would try to analysis the expect acquire requests when users randomly select one slot to send their request.

Notation:

Q: the expect acquire request

R: the number of slots

K: the number of users

i: the number of acquire requeset

m: the number of collsion slots

G(a,b): the number of combinations when a users collide in b slots

X(m)={x_1, x_2,..., x_m}, x_j represents collsion user number in j_{th} collsion slots

When the collsion happens on one slot, it means that at least two users send their requests in the slot. Then:

$$x_j \geq 2, \text{j} = 1,2,\ldots,\text{m}$$

We firstly ananlysis G(a,b). When a users happen collsion in b slots, we sequentially choose some users from the slot x_1 to x_b. The maximum user number in the slot x_j is $a - 2(b-j) - \sum_{k=1}^{j-1} x_k$ that we should deduct the total choosing number of x_1 to x_{j-1} and the reserverd users for x_{j+1} to x_b. Then, we can write the equation as below :

$$\text{G(a,b)} = \left\{\sum_{x_1=2}^{a-2(b-1)} \binom{a}{x_1} \left\{\sum_{x_2=2}^{a-2(b-2)-x_1} \binom{a-x_1}{x_2} \cdots \left\{\sum_{x_{b-1}=2}^{a-2-\sum_{j=1}^{b-2} x_j} \binom{a-\sum_{j=1}^{b-2} x_j}{x_{b-1}} \right\} \right\} \right\}$$

Then, we analysis the expect acquire request Q. When we get i requests from K users, we firstly choose i users from K users and choose i slots that these users send his request from R slots. It also means that the residual K-i users happen collsion in some slots and the maximum number of collsion slots is $\lfloor (K-i)/2 \rfloor$ that the user number in every collsion slots is just two users. Therefore, we can wirte the equeation as below:

$$P\{Q=1\}=\frac{\binom{K}{1}\binom{R}{1}(G(K-1,1)+G(K-1,2)+\cdots+G(K-1,\lfloor(K-1)/2\rfloor))}{R^K}$$

$$P\{Q=2\}=\frac{\binom{K}{2}\binom{R}{2}(G(K-2,1)+G(K-2,2)+\cdots+G(K-2,\lfloor(K-2)/2\rfloor))}{R^K}$$

…

P{Q=K-1}, no such case

$$P\{Q=K\}=\frac{\binom{K}{K}\binom{R}{K}}{R^K}$$

The expect acquire request is:

$$E[Q] = \sum_{i=1}^{K} P\{Q=i\} * i$$

Finally, according to the realtion between R and K, the maximum acquire requests and maximum collision slots are different, we write the equation as below:

R ≥ K ,

$$E[Q] = \frac{\sum_{i=1}^{K}\binom{K}{i}P_i^R\sum_{m=1}^{\lfloor(K-i)/2\rfloor}\binom{R-i}{m}\,G(K-i,m)}{R^K}\,i$$

Because user number is less than slot number, the maximum acquire requests is K and the maximum collsion slots is $\lfloor(K-i)/2\rfloor$.

R < K , R $> \left\lfloor\frac{K}{2}\right\rfloor$

$$E[Q] = \frac{\sum_{i=1}^{R-1}\binom{K}{i}P_i^R\sum_{m=1}^{\min\{R-i,\lfloor(K-i)/2\rfloor\}}\binom{R-i}{m}\,G(K-i,m)}{R^K}\,i$$

Because user number is bigger than slot number, the maximum acquire requests is R-1. The maximum collsion slots is $min\{R-i,\lfloor(K-i)/2\rfloor\}$ because we should deduct the i occupied slots of acqire requests.

R < K , R $\leq \left\lfloor\frac{K}{2}\right\rfloor$,

$$E[Q] = \frac{\sum_{i=1}^{R-1}\binom{K}{i}P_i^R\sum_{m=1}^{R-i}\binom{R-i}{m}\,G(K-i,m)}{R^K}\,i$$

Because user number is bigger than slot number, the maximum acquire requests is R-1. The maximum collsion slots is $R-i$ because the maximum collsion slots would exceed the total slot number.

4.7 System Flow Chart

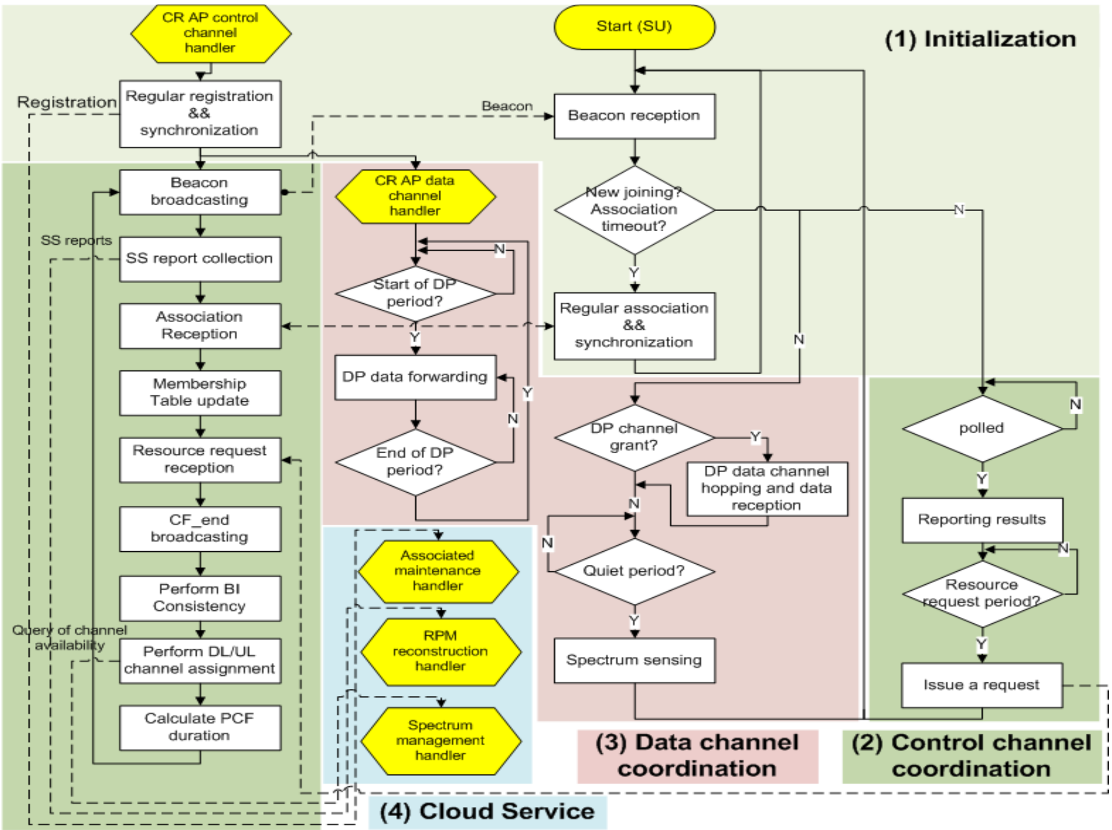

Fig17. System flow chart of proposed CR MAC

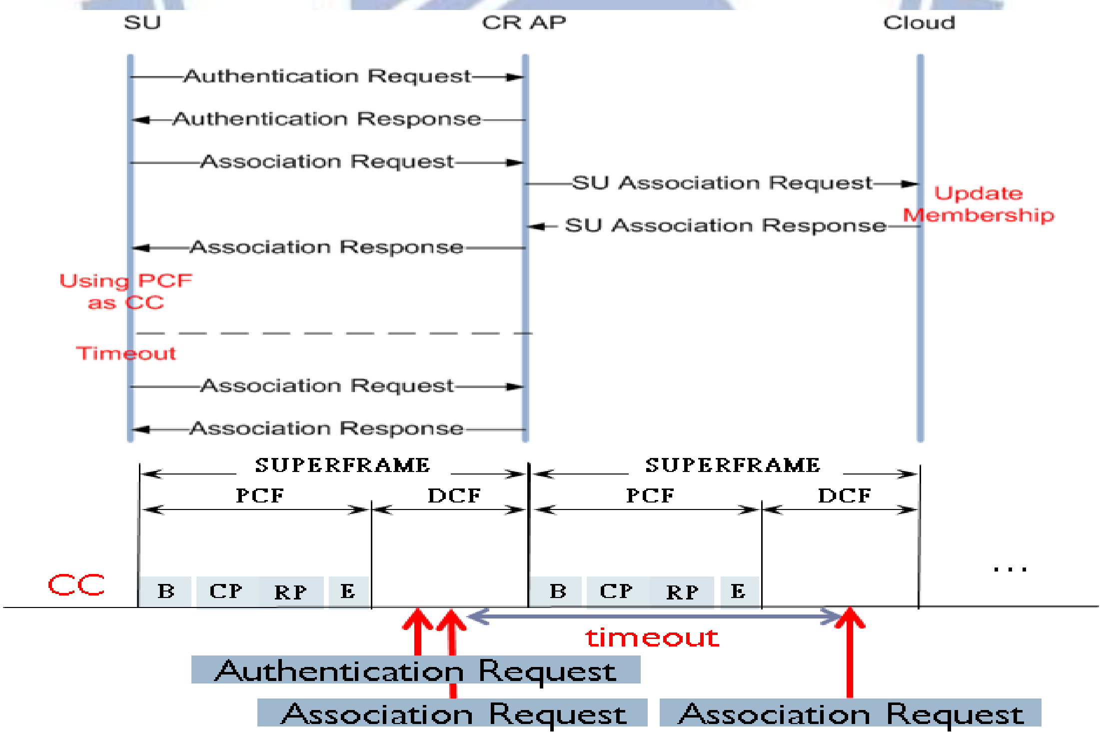

Fig.18. The association procedrue of SUs

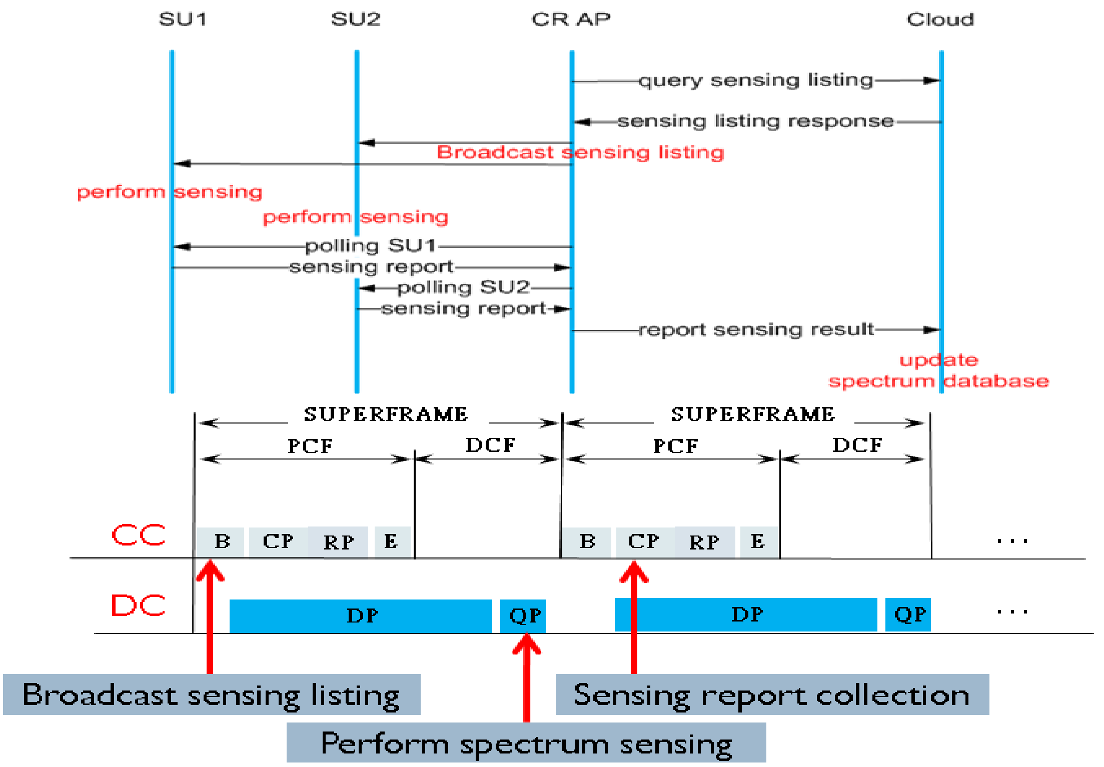

Fig19. Specturm sensing and sensing report procedure

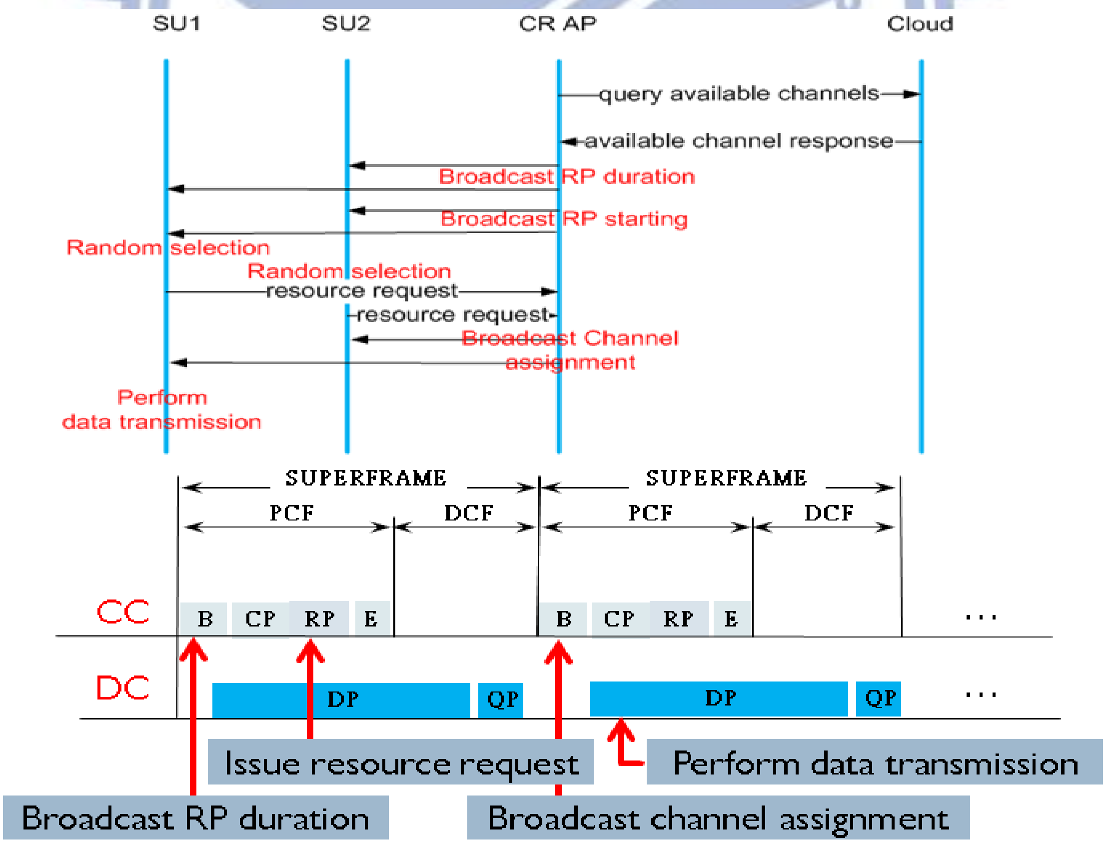

Fig20. Resource request issue and data transmission procedure

5. Throughput Analysis

We firstly base on the proposed CR MAC architecture to analysis the CR network throughput. Futher, we extend the throughput analysis equation of WIFI network include the impaction of SUs. That, we derivate the throughput equation from the throughput analysis of “ Performance Analysis of IEEE 802.11 Distribution Coordination Function”. The author proposes throughput analysis for saturation WIFI user throughput. Finally, we base on the throughput influence threshold of WIFI network and the accuracy threshold of spectrum sensing evalution algorithm to calculate the maximum system throughput that includes WIFI network and CR network.

5.1 CR Throughput Analysis

Notation:

N: the number of data channels

K: the number of SUs

R: the number of acquiring resource request in this SUPERFRAME

n_{DP}: the number of frame per data period

$r_{i,j}$: the data rate of user *j* on the channel *i*

s_i: the number of sensing samples of channel *i*

$S(\alpha, s_i)$: the accuracy bases on the sensing time α and sensing report number s_i of channel *i*

$C(T\ ,\ T_{PCF}\ ,\ N\ ,\ K)$: the throughput of cognitive radio network

F(R, N, K): scheduling function bases on the request number *R* and the channel number *N*

$$F(R, N, K) = \begin{bmatrix} x_{1,1}, x_{1,2}, \dots, x_{1,k} \\ x_{2,1}, x_{2,2}, \dots, x_{2,k} \\ \dots \\ x_{N,1}, x_{N,2}, \dots, x_{N,k} \end{bmatrix}$$

Where,

- $x_{i,j} = \begin{cases} 0\ ,\ channel\ i\ isn't\ assigned\ to\ user\ j \\ 1 \sim n_{DP}, channel\ i\ is\ assigned\ \ to\ user\ j \end{cases}$, $i =$

$1,2,\ldots,N \quad , j = 1,2,\ldots,K$

- $\sum_{j=1}^{K} x_{i,j} \leq n_{DP} \ , \ i = 1,2,\ldots,N$

Then, CR Throughput can be written as below:

$$C(T\ ,\ T_{PCF}\ ,\ N\ ,\ K) = \frac{\sum_{i=1}^{N} S(\alpha,s_i) \sum_{j=1}^{K} x_{i,j} \cdot \frac{T-(t_{beacon}+t_{QP})}{n_{DP}} \cdot r_{i,j}}{T}$$

5.2 WIFI Throughput Analysis

Notation

M: the number of WIFI users in the WIFI network

K: the total number of SUs in the network

k: the number of SUs in the WIFI network

r: the transmit probability of user in the WIFI network

Ts: the transmit time of data packet

Tas: the transmit time of associated packet

Tc: the collision time caused by users data transmission at the same time

E[P]: the expected user data packet size

σ: the slot time

p_{tr}: the probability that at least one user transmits his data

p_M: the probability that only one WIFI user transmits his data

p_k: the probability that only one SU transmits his data

S_k : the system throughput of WIFI network with k SU in the network

S : the system throughput of WIFI network

In the following, we would introduction how to calculate the WIFI throughput. We assume there exist some WIFI users and both of them always have date to transmit (saturation) in the network. Then, there also exist some CR users that would send association request in the network. We derivate the throughput equation from the throughput analysis of [13] that the author proposes a throughput analysis equation for saturation WIFI users throughput.

Then, the WIFI throughput can be written as below:

- $p_{tr} = 1 - (1-r)^{M+k}$

- $p_M = \frac{Mr(1-r)^{M+k-1}}{p_{tr}} = \frac{Mr(1-r)^{M+k-1}}{1-(1-r)^{M+k}}$
- $p_k = \frac{kr(1-r)^{M+k-1}}{p_{tr}} = \frac{kr(1-r)^{M+k-1}}{1-(1-r)^{M+k}}$
- $S_k = \frac{p_{tr}p_M E[P]}{(1-p_{tr})\sigma+p_{tr}p_M T_s+p_{tr}p_k T_{as}+p_{tr}(1-p_M-p_k)T_c}$

The WIFI throughput is according to the probability of that there are k SUs in the WIFI network

- $S = \sum_{k=0}^{K}\left(\frac{1}{t_{timeout}}\right)^{k}\left(1-\frac{1}{t_{timeout}}\right)^{K-k} S_k$

5.3 System Throughput

Notation

M: the number of WIFI users

K: the number of SUs

N: the number of data channels

δ_w: the throughput influence threshold for WIFI network

δ_s: the accuracy threshold of spectrum evaluation algorithm

α: the sensing time to acquire one sample.

g: the number of channel and SU group

k_i: the number of SUs in the i_{th} group

n_i: the number of sensing channels in the i_{th} group

n_d: the number of available TVB channels

m: the number of sensing sample per data channel

s : the probability of report error

T_{DCF}: the duration of DCF mode

T_{PCF}: the duration of PCF mode

$T_{PCF,max}$: the maximum duration of PCF mode

$T_{PCF,residual}$: the residual duration of PCF mode

K_{max}: the maximum number of polling SUs in PCF mode

K_{min}: the minimum number of polling SUs in PCF mode

K_{coe}: the maximum coexistence number of polling SUs in PCF mode

$W(T-T_{PCF},M)$: the throughput of WIFI network

$C(T,T_{PCF},N,K)$: the throughput of cognitive radio network

z: the throughput of all the networks

Problem description:

We try to find the maximum throughput of CR network and WIFI network, and there is a tradeoff between CR throughput and WIFI throughput because of the PCF mode duration. The other tradeoff is between the channel sensing time and sensing report time. If more users sense the channels simultaneously, it would decrease the QP duration but increase the CP duration. Because the sensing time per sample (10ms) is greater than report time per user (500us), we have to decrease the QP duration as possible to acquire maximum throughput.

Assume:

We assume that we can query cloud for the number of sensing sample per channel m, the number of sensing channel n_i, and the number of SU k_i in every group. Without loss the generality, we also assume the number of sensing channel is less than the number of user in every group and the maximum number of polling SUs in PCF mode would less than the number of SUs per group:

$$n_i \leq k_i \ and \ K_{max} \leq k_i, i = 1,2, \dots, g$$

Calculate Procedure:

We first calculate the maximum duration of PCF mode and the system throughput that is based on the influence threshold δ_w.Then, decrease the maximum duration of PCF mode, calculate the new system throughput, and check if increase the throughput or not till the duration is equal to zero. Finally, we can acquire the maximum system throughput and the duration of every period that is based on the sensing accuracy threshold δ_s and throughput influence threshold δ_w.

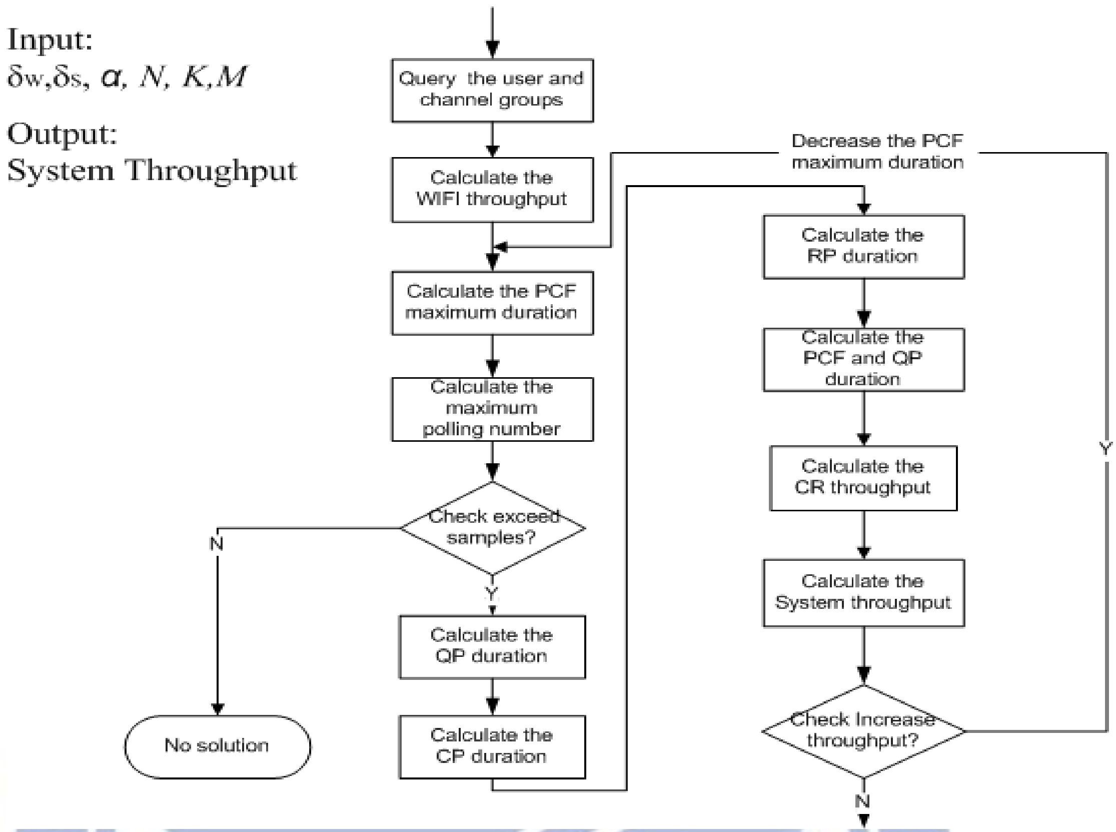

Fig21. flow chart of calculating procedure

Input: δ_w, δ_s, α, N, K, M, $t_{timeout}$, T

1) query cloud for the sensing samples per channel *m*, the number of sensing channels n_i, and the SU groups k_i by δ_s

2) the WIFI throughput

$$S(M, K, t_{timeout}) = \sum_{k=0}^{K} \left(\frac{1}{t_{timeout}}\right)^{k} \left(1 - \frac{1}{t_{timeout}}\right)^{K-k} S_k$$

3) calculate the maximum duration of PCF, $T_{PCF,max}$

$$S - S\frac{T_{DCF}}{T_{DCF}+T_{PCF}} \leq \delta_w, \text{ and } T = T_{DCF} + T_{PCF}$$

4) calculate the maximum polling number, K_{max} and K_{coe}

$$T_{PCF,residual} = T_{PCF,max} - t_{Beacon} - t_{CF\_end}$$

$$K_{max} = \left\lfloor \frac{T_{PCF,residual}}{t_{poll} + 2t_{SIFS} + t_{sense}} \right\rfloor$$

If $K_{coe} \geq K_{max} \geq m$, go to (5)

Else if $K_{max} \geq K_{coe} \geq m$, $K_{max} = K_{coe}$ or decrease $t_{timeout}$, go to (5)

Else if $K_{max} \geq$ m $\geq K_{coe}$, decrease $t_{timeout}$, go to (5)

Else, no solution

5) calculate the actual duration of t_{QP}

$$t_{QP} = \left\lceil \frac{nm}{K_{max}} \right\rceil * \alpha$$

6) calculate the duration of t_{CP}

If $\left\lceil \frac{nm}{K_{max}} \right\rceil \leq 1$,

$$t_{CP} = nm[(1-s)\cdot(t_{poll} + 2\cdot t_{SIFS} + t_{sense}) + s\cdot(t_{poll} + t_{PIFS})]$$

Else, find the minimum number of polling users

$$K_{min} = \left\lceil \frac{nm}{\left\lceil \frac{nm}{K_{max}} \right\rceil} \right\rceil$$

$$t_{CP} = K_{min}[(1-s)\cdot(t_{poll} + 2\cdot t_{SIFS} + t_{sense}) + s\cdot(t_{poll} + t_{PIFS})]$$

7) calculate the actual duration of t_{RP}

$$T_{PCF,residual} = T_{PCF,max} - t_{Beacon} - t_{CP} - t_{CF\_end}$$

$$n_{RP,1} = \left\lfloor \frac{T_{PCF,residual} - t_{poll} - 2\cdot t_{SIFS}}{t_{request}} \right\rfloor$$

$$n_{RP,2} = argmin\, R(x, K-k) \geq n_d$$

$$t_{RP} = t_{poll} + min\{n_{RP,1}, n_{RP,2}, K-k\}\, t_{request} + 2 \cdot t_{SIFS}$$

8) calculate the actual duration of T_{PCF}, and the duration of T_{DCF},

$$T_{PCF} = t_{beacon} + t_{CP} + t_{RP} + t_{CF_{end}}$$

$$T_{DCF} = T - T_{PCF}$$

9) calculate the duration of t_{DP}, and the CR throughput

$$C(T, T_{PCF}, N, K) = \frac{\sum_{i=1}^{N} S(\alpha, s_i) \sum_{j=1}^{k} x_{i,j} \cdot \frac{T-(t_{beacon} + t_{QP})}{n_{DP}} \cdot r_{i,j}}{T}$$

10) calculate the System throughput

$$z = S\frac{T_{DCF}}{T_{DCF}+T_{PCF}} + C(T, T_{PCF}, N, K)$$

6. Analysis Result

In this section, we would show the analysis result. We divide into three parts (1) SU coexistence (2) WIFI throughput with SUs (3) System throughput. The duration of SUPERFRAME is 400ms. The required sensing sample per channel is 5 to achieve the accuracy 0.9. The transmission rate is 11Mbps, basic rate is 1Mbps, and the average packet size of WIFI user is 1500 bytes. The TVB channel bandwidth is 6MHz, the channel SNR is 10dB. The packet size of BEACON is 464bits, CF_END is 160 bits, POLL is 160 bits, resource request is 32 bits, and sensing report is 32+sensing channel*4*8 bits.

The following is the residual WIFI parameter setting:

Parameter	Length
MAC header	224 bits
PHY header	192 bits
SIFS	10 us
DIFS	50 us
EIFS	358 us
PIFS	30 us
Slot time	20 us
ACK	304 bits
Maximum retry count	7
CW_{min}	32
CW_{max}	1024

Fig22. 802.11 parameter setting

6.1Maximum Coexistence SUs

We first give the value of WIFI user, timeout, and average packet size, and find the maximum coexistence SUs. The analysis result show coexistence number decrease with increasing packet size and increase with increasing timeout.

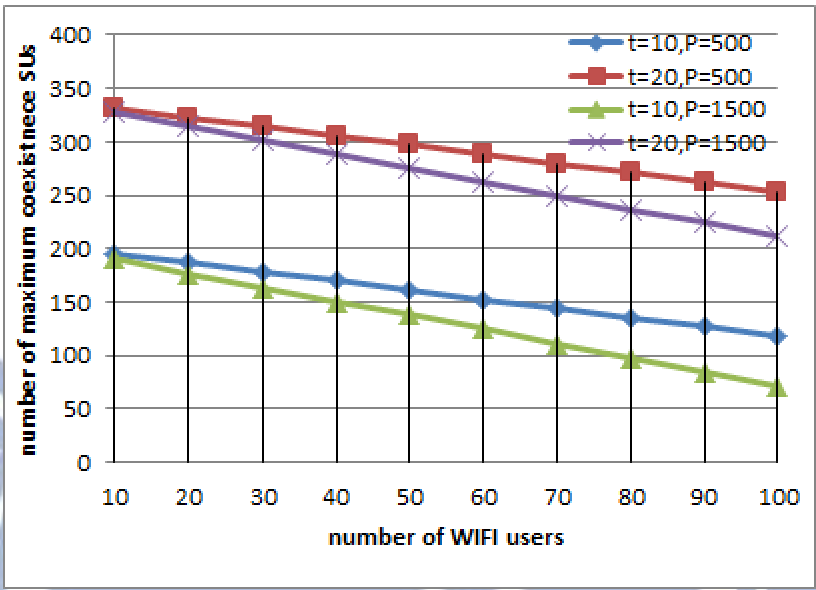

Fig23. Maximum coexistence SUs with different packet size and timeout

Then, we want to know the coexistence SUs with different access scheme of WIFI users. The analysis result show the coexistence SUs in RTS/CTS scheme is smaller than basic scheme, but is large than basic scheme with lots of WIFI users.

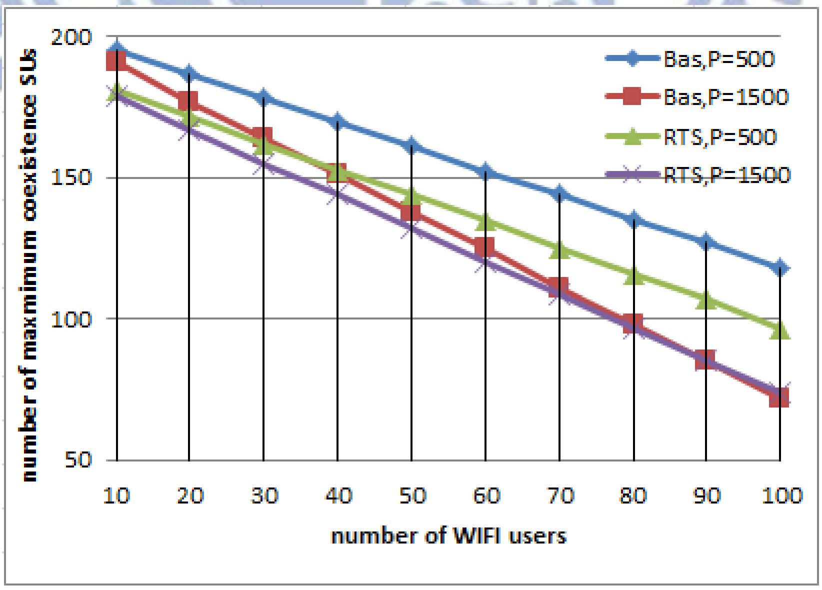

Fig24. Maximum coexistence SUs with different access scheme

6.2WIFI Throughput with SUs

We want to know when there exist some SUs in the WIFI network, the impact to the WIFI throughput. We first show the traditional throughput that doesn't exist SUs. Then, calculate the throughput when give the different value of WIFI users, SUs, and timeout. The analysis result show the impact to WIFI throughput increase when decrease timeout and increase coexistence SUs. But the impact is not obvious to WIFI throughput.

Basic Access

M	traditional	SU=50,t=1	SU=50,t=10	SU=100,t=1	SU=100,t=10
10	5.82198	5.82154	5.82194	5.8211	5.8219
30	5.07402	5.07388	5.074	5.07374	5.07399
50	4.6889	4.68882	4.6889	4.68874	4.68889

Fig25. WIFI throughput with coexistence SUs by basic access

The throughput impact in RTS/CTS is also not obvious to WIFI throughput

RTS/CTS Access

M	traditional	SU=50,t=1	SU=50,t=10	SU=100,t=1	SU=100,t=10
10	4.70566	4.7053	4.70559	4.7053	4.70559
30	4.48614	4.48602	4.48612	4.48602	4.48612
50	4.35001	4.34994	4.35	4.34994	4.35

Fig26. WIFI throughput with coexistence SUs by RTS/CTS access

Through the analysis result, we know the impact of coexistence SUs is little for WIFI throughput no matter we adopt basic access scheme or RTS/CTS access scheme.

6.3 System Throughput

We calculate the system throughput in this section. Give M=20, K=20, timeout=10s, packet size =1500 bytes. The report error probability s =0.1, and we want to know the impact to system throughput when we give different value of WIFI throughput impact. When the throughput threshold increases, we can poll more SUs for collecting sensing report. That is, we just need fewer sensing time of QP, and increase the CR throughput. When we increase the impact threshold, we can find the suitable PCF duration for sensing report and request issue.

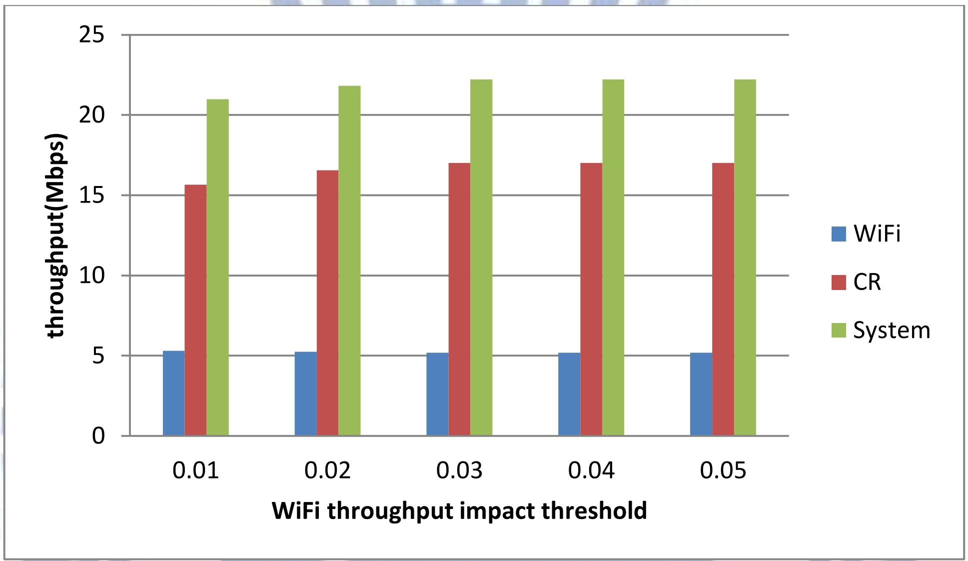

Fig27. System throughput1

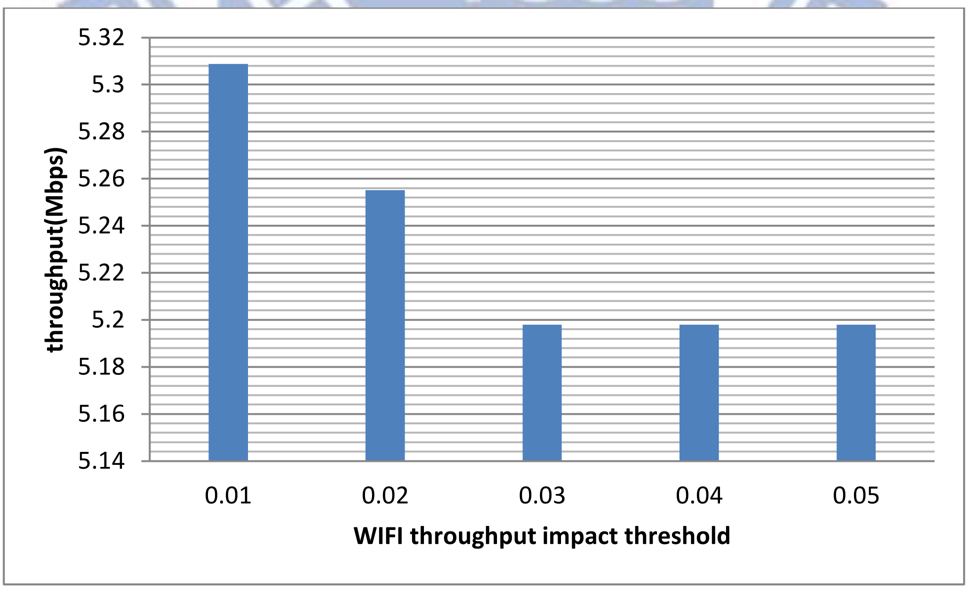

Fig28. WIFI throughput in system throughput1

Then, Give M=20, K=20, timeout=10s, packet size =1500 bytes, and impact threshold is 0.1. We want to know the impact for system throughput when the report error probability increases. Through the analysis result, we can see that we need to poll more SUs to acquire the require number of sensing report and it would cause more PCF duration. That is, decrease the WIFI throughput. In the other hands, we also need more sensing time of QP for sensing report and decrease the CR throughput.

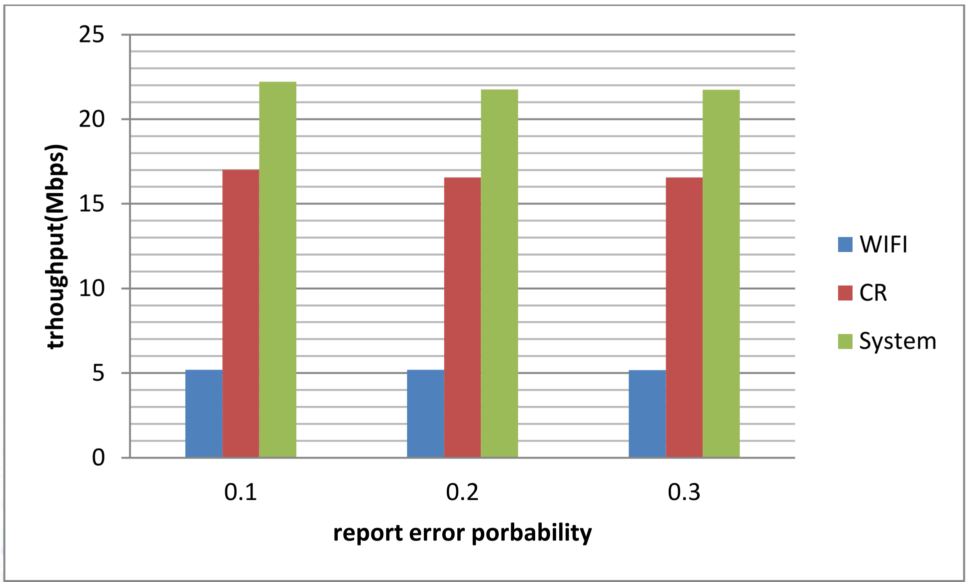

Fig29. System throughput2

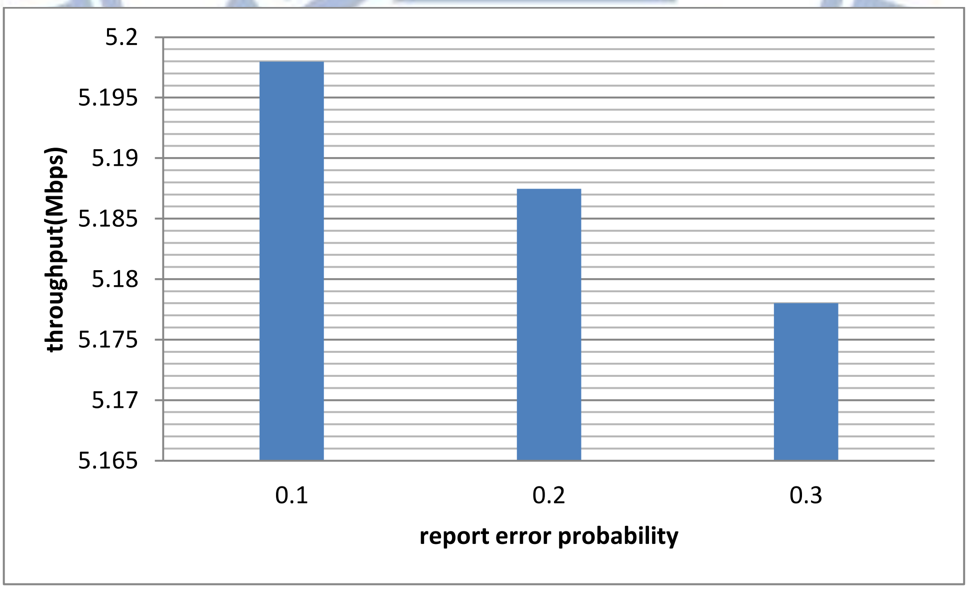

Fig30. WIFI throughput in system througput2

Then, Give M=20, timeout=10s, packet size =1500 bytes, impact threshold is 0.1, and report error probability 0.1. The sensing channel is 8 and available channel is 1. We want to know the impact to throughput with different SU number. When SU number increases, more SUs could sense channel at the same time. It needs fewer channel sensing time, and increase the CR throughput.

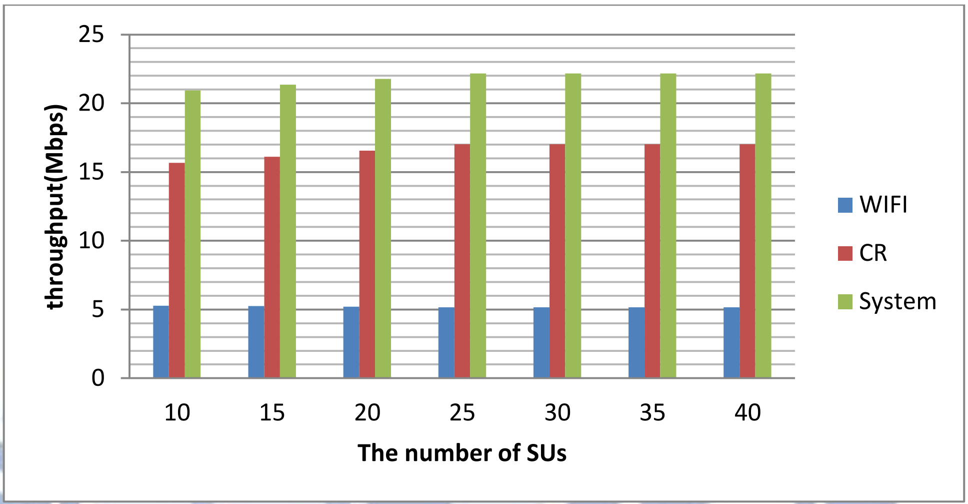

Fig31. System throughput with different SU number

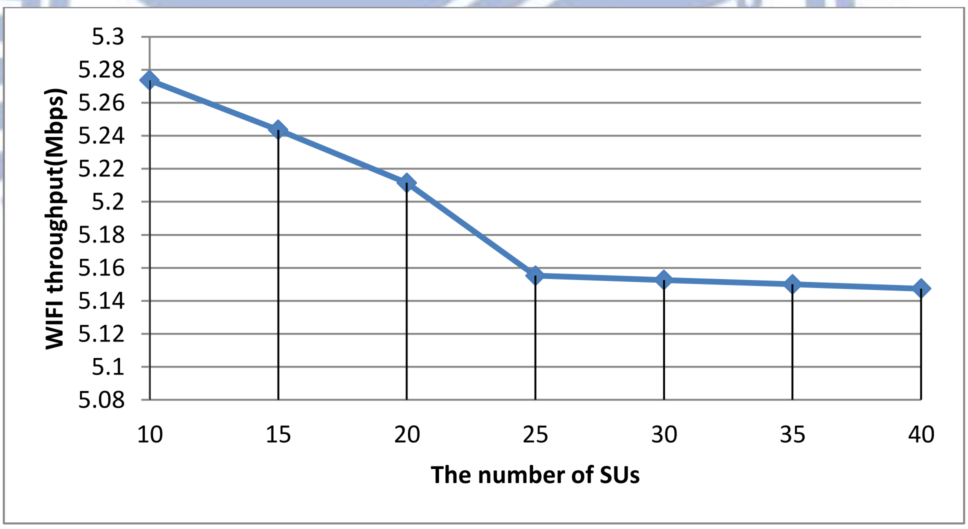

Fig32. WIFI throughput with different SU number

SU	10	15	20	25	30	35	40
CP(s)	0.05615	0.06707	0.089	0.13288	0.13288	0.13288	0.13288
RP(s)	0	0.01152	0.01347	0.01152	0.01347	0.01541	0.01736
QP(s)	0.05	0.04	0.03	0.02	0.02	0.02	0.02

Fig33. The duration of every period with different SU number

Then, give K=20, timeout=10s, packet size =1500 bytes, impact threshold is 0.1, and report error probability 0.01. The sensing channel is 8, and PCF duration is 0.011339s. We use the ns-2 simulator to validate the WIFI analysis result. The simulation result doesn't match the analysis result because the analysis result doesn't consider the packet transmit error probability and other control message. The simulation result is close to analysis result, so we could consult the result to design our real CR-MAC duration.

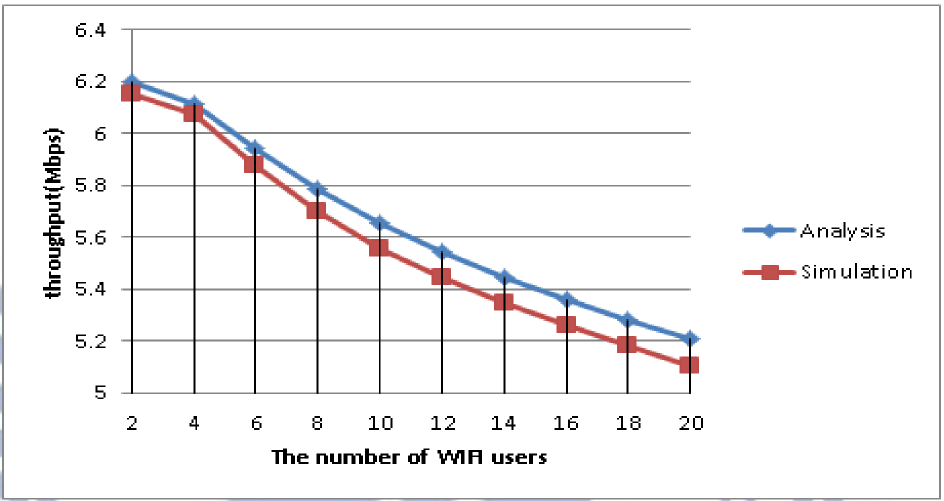

Fig34. The comparison with different number of WIFI users

We set the queue length 50 packets, and all WIFI users are saturation. The time of queue delay increase with the number of WIFI users, because more and more user content and use the channel.

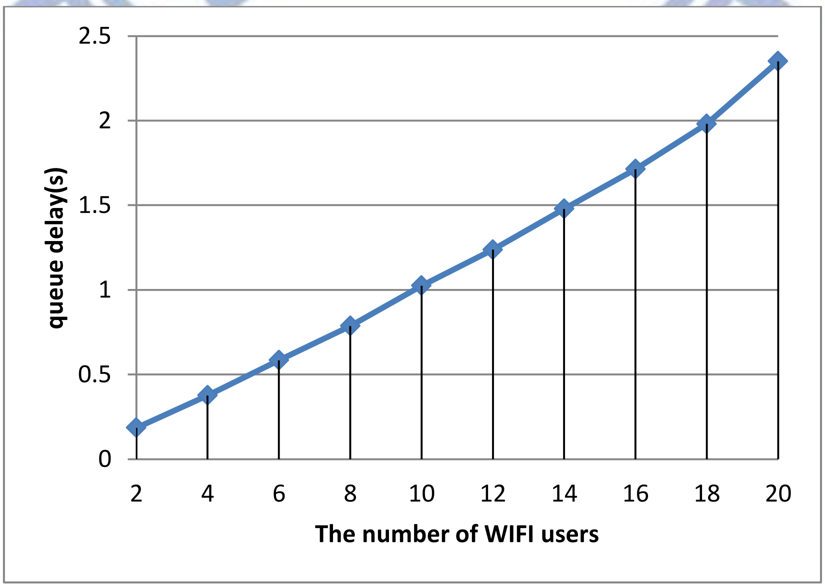

Fig35. Queue delay with different number of WIFI users

7 Conclusion and Future Work

In this paper, we use the ISM band for control channel realization for CR network, and we analysis the impaction to the WIFI network. We discuss the coexistence problem that includes interval consistence and maximum coexistence user number. The analysis result is close to simulation result, and we can use the analysis result to design the real CR MAC protocol.

In the future, we would discuss more efficient cooperative spectrum sensing and sensing report policy. In the other hand, we also discuss more efficient resource request acquire policy. Then, not only extend the SUs to use the ISM band, but also extend the WIFI users to use the TVWS for the heterogeneous network. That, design a hybrid MAC protocol coexists between CR network and WIFI network.

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