Postprint of FQMAC Protocol Based on Principles of Secondary User Channel Usage Fairness and QoS Guarantee

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Abstract

For the coexistence of heterogeneous cognitive radio networks, the FQMAC (fair and QoS guaranteed MAC) protocol is proposed. The protocol adopts beacon frame synchronization to divide time into beacon periods, within which channel sensing, channel negotiation, and data transmission are performed separately. Channels occupied by secondary users from other heterogeneous networks are also treated as available channels. All available channels are classified into different levels based on channel quality, and secondary users are classified into different levels based on their traffic characteristics. Higher-level secondary users have priority to reserve higher-level channels. The appropriate duration of the channel negotiation phase is theoretically analyzed by establishing a Markov chain model, and the theoretical value for its appropriate duration is derived. Simulation results demonstrate that FQMAC can effectively improve network throughput, guarantee users' QoS (Quality of Service), and achieve good fairness.

Full Text

Preamble

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FQMAC Protocol: Fair Channel Usage and QoS Guarantee Principles for Secondary Users

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Abstract: This paper proposes the FQMAC (Fair and QoS Guaranteed MAC) protocol for scenarios where heterogeneous cognitive radio networks coexist. Time is divided into beacon periods using beacon frame synchronization, with each period comprising channel sensing, channel negotiation, and data transmission phases. Channels occupied by secondary users from other heterogeneous networks are also treated as available channels. All available channels are classified into different levels based on channel quality, and secondary users are classified into different levels based on their traffic characteristics. High-level secondary users are given priority to reserve high-level channels. The reasonable duration of the channel negotiation phase is theoretically analyzed by establishing a Markov chain model, yielding its theoretical value. Simulation results demonstrate that FQMAC can effectively improve network throughput, guarantee users' QoS (Quality of Service), and achieve better fairness.

Keywords: heterogeneous; cognitive radio networks; classification; QoS guarantee; fairness

0 Introduction

Fixed spectrum access strategies are still widely used in wireless communication, resulting in low utilization of licensed spectrum. Meanwhile, available spectrum resources have been largely allocated, leaving some unlicensed users with insufficient spectrum resources. Cognitive radio technology has emerged to address this issue by allowing secondary users (unlicensed users) to opportunistically access temporarily unused licensed spectrum during primary users' communication idle periods. This improves spectrum utilization without affecting primary users. However, no internationally unified communication protocol standard currently exists for cognitive radio, and since control and coordination over wireless channels occur at the MAC (Media Access Control) layer, designing a good MAC protocol is crucial for CRN (Cognitive Radio Network) performance.

Research on MAC protocols for cognitive wireless networks is currently a hot topic, with numerous experts focusing on this area and various types of MAC protocol designs having been proposed. For example, the authors in [?] proposed a MAC protocol based on spectrum prediction technology that employs a statistical channel allocation strategy to improve throughput and reduce interference with primary users. Manyi et al. proposed an adaptive preamble sampling-based MAC protocol called APS-MAC for CRSN (Cognitive Radio Sensor Network) [?], which supports opportunistic spectrum access while addressing energy consumption issues in CRSN. Nafees et al. proposed a cross-layer MAC protocol called RAPE for cognitive radio ad hoc networks [?], which achieves good performance by maintaining a small number of clusters and a stable number of common channels. Wu et al. proposed a neighbor-aware distance estimation MAC protocol called NMAC for CRAHN (Cognitive Radio Ad Hoc Networks) [?], where the distance estimated through neighbor-aware sensing between SU (secondary user) communication pairs is used to control transmitter power, thereby mitigating hidden and exposed terminal problems in multi-channel CRAHN, increasing throughput, and reducing PU (primary user) interruption probability.

Some MAC protocols are designed based on channel negotiation mechanisms. Such protocols maintain a CCC (Common Control Channel) and pre-negotiate and reserve data channels through the CCC. Examples include the database-driven MAC protocol for CM2M networks proposed in [?], the dynamic control channel MAC protocol DCC-MAC proposed in [?], and the synchronous MAC protocol OMC-MAC using CCC proposed in [?]. However, none of these MAC protocols consider the coexistence of heterogeneous CRNs. A heterogeneous CRN refers to networks employing different network access technologies or different communication protocols. Currently, there is no unified communication standard for CRN, and different local area networks adopt different communication rules with diverse hardware devices, leading to CRN heterogeneity [?]. With the development of 5G networks and the Internet of Things, scenarios with coexisting heterogeneous networks will become increasingly common, placing higher demands on network communication protocols. CRN, with its unique adaptability and intelligence advantages, will undoubtedly be an important component of next-generation communication networks. Therefore, this paper focuses on the coexistence of heterogeneous CRNs, examining how to achieve efficient communication, fairness, and QoS support in such scenarios.

Reference [?] first considered the coexistence of different CRNs. As described, two heterogeneous CRNs may use different transmission waveforms, making it impossible for secondary users in one CRN to recognize waveforms from another CRN. If a licensed channel is occupied, the current secondary user only knows the channel is busy but cannot determine whether it is occupied by a primary user or a secondary user. Most existing MAC layer protocols adopt a two-state channel model, classifying channels as either busy or idle. Consequently, if a secondary user detects a busy channel, it can only assume the channel is occupied by a primary user and simply abandons it. However, the channel might actually be occupied by a secondary user from another CRN, which harms fairness among secondary users. To address this, [?] first proposed a three-state channel model, further dividing the "busy" state into "primary user occupied" and "secondary user occupied" states. The paper also designed a sensing algorithm called distance estimation detection to determine which of the three states the current channel is in. Based on this three-state channel model, [?] designed FMAC, where SU nodes following the FMAC protocol use the distance estimation algorithm [?] to determine whether a busy channel carries primary user signals or secondary user signals. If it is the latter, they employ a competition mechanism to compete for channel usage, improving fairness among secondary users.

Although FMAC improves fairness, frequent competition among secondary users reduces channel throughput to some extent. Moreover, FMAC overemphasizes competition while neglecting the full utilization of idle channels. Additionally, the algorithm lacks QoS awareness and guarantee mechanisms, failing to meet the delay requirements of some users. Therefore, this paper introduces the

three-state model and uses beacon frame synchronization to design a new MAC protocol called FQMAC. FQMAC borrows the contention-free data transmission phase concept from [?], designing the data transmission phase as partially contention-free. Building upon this, it proposes channel classification and user classification mechanisms, providing targeted QoS guarantees for secondary users in the network. This paper also establishes a Markov chain model for theoretical analysis to derive the reasonable duration of the channel negotiation and reservation phase. Simulation experiments demonstrate that the proposed design improves channel utilization to a certain extent, maintains fairness among secondary users, increases network throughput, effectively reduces channel access delay for users with high QoS requirements, and guarantees service quality.

1 FQMAC Protocol Design

Unlike most existing literature, this paper considers the coexistence of multiple heterogeneous CRNs. This heterogeneity was also mentioned in the FMAC paper [?]. When channels are occupied by secondary users from heterogeneous networks, FMAC allows secondary users to compete with the occupying secondary users for channel usage, thereby increasing fairness among secondary users. However, this protocol causes frequent competition among secondary users, reducing channel throughput to some extent. Moreover, FMAC purely emphasizes competition without addressing how to effectively utilize idle channels. Therefore, this paper divides time on channels into three periodic phases (with the data transmission phase being contention-free), designs the FQMAC protocol for heterogeneous CRNs, which can reduce some competition while providing different QoS support for different secondary users in the network, all while ensuring fairness among secondary users.

From feasibility and economic perspectives, this paper assumes each SU node has a half-duplex transceiver. The protocol design employs a control information exchange mechanism (RTS-CTS mechanism) and beacon frame synchronization mechanism, which reserves channels first and then has neighbor nodes set their NAVs accordingly, thereby avoiding hidden terminal problems. This paper assumes there is a global CCC (common control channel) within the CRN for exchanging control information.

1.1 Beacon Period Structure

Time frames are divided into periodic beacon intervals (BI). SUs are synchronized by periodic beacon signals. Whenever an SU wants to join the network, it first listens to at least one beacon frame signal on the CCC to synchronize itself with the rest of the network. If it never hears a beacon frame signal, it begins sending periodic beacon frame signals itself as the first node of this CRN, allowing subsequently joining nodes to synchronize with it [?]. The BI is divided into three phases: sensing phase, CCC channel contention phase (channel negotiation phase), and data transmission phase. Figure 1 [Figure 1: see original paper] shows the time structure of each beacon cycle.

1.2 Channel Sensing

As shown in Figure 1, the FQMAC protocol specifies that the first phase in each beacon interval is the channel sensing phase, during which SU nodes detect available channels to obtain the latest channel information. In the sensing phase, the FQMAC protocol stipulates that all SUs must stop transmitting to ensure sensing results are not interfered with by surrounding SUs. Each SU independently senses channels and obtains a list of all available channels after the sensing phase, storing this list in the current SU node.

Assume there are network A and network B, both cognitive radio networks that can use licensed bands in a cognitive manner. Assume nodes in network A adopt the FQMAC algorithm proposed in this paper, while network B adopts other cognitive network protocols. These two networks are heterogeneous networks. FQMAC uses beacon frame synchronization to divide time into beacon periods, performing channel sensing, channel negotiation, and data transmission within each period. Therefore, during the channel sensing phase, users in network A stop sending and enter the channel sensing state. Since network B is a heterogeneous network, many nodes in network B may still be in communication transmission state while network A nodes are sensing channels. Assume a pair of nodes in B is currently using a licensed channel H5 for data transmission and reception. Network A nodes can sense both idle licensed channels and the licensed band H5 occupied by secondary users. For this situation, ordinary cognitive networks can only distinguish whether a licensed band is idle or occupied, so their strategy is to use only idle channels and abandon the use of channel H5. This creates unfairness regarding licensed channel H5 because the nodes currently using it are not primary users. A fair approach would be for users in network A to compete with secondary users in network B for licensed channel H5. Therefore, the FQMAC protocol also adopts the distance estimation algorithm [**?**] to distinguish between primary users and secondary users.

1.2.1 Channel Classification Mechanism The main feature of the FQMAC protocol is its channel classification and user classification mechanisms. The channel classification mechanism works as follows: during the sensing phase, FQMAC uses energy detection technology and the distance estimation detection algorithm [**?**] to detect the channel state, then processes the sensing results accordingly: (a) filters out channels occupied by primary users; (b) treats channels occupied by secondary users from heterogeneous CRNs as level-2 available channels and adds them to the available channel list; (c) treats idle channels as level-1 available channels and adds them to the available channel list. Thus, the available channel list maintained by SU nodes contains two types of available channels: level-1 and level-2, allowing the MAC protocol to allocate suitable channels to secondary users based on their characteristics.

1.2.2 Channel Negotiation and Reservation Each SU with data frames to send must participate in the competition for the common control channel CCC to engage in channel negotiation and reservation. This process occurs in the second phase of the beacon period, the channel negotiation phase. The FQMAC protocol abandons the classic binary exponential backoff algorithm in IEEE 802.11 DCF (Distributed Coordination Function) and instead adopts a fixed window backoff algorithm (named FWSB algorithm), which will be detailed in Section 1.2.4. The position of the competition phase in the beacon cycle is shown in Figure 1.

1.2.3 Secondary User Classification Mechanism To meet the needs of users with different QoS requirements, this paper designs a user classification mechanism. Its main idea is that based on secondary user nodes' awareness of their own traffic data characteristics, they are classified into three levels according to their delay and transmission quality (packet loss rate) requirements:

a) Level 1: Secondary users transmitting time-sensitive data such as alarm information with high delay requirements.

b) Level 2: Users transmitting general information with moderate delay requirements.

c) Level 3: Users transmitting video, backup files, etc., with low requirements for packet loss rate or delay.

To differentiate secondary users, this paper chooses to divide them into three levels. This number can be adjusted based on specific circumstances. If the specific network operates in different time and space domains, the network environment and characteristics may vary, as may the stringency of communication quality requirements. In such cases, corresponding adjustments can be made. However, this paper selects three levels based on scenarios applicable to most common situations.

1.2.4 FWSB Backoff Algorithm in Channel Negotiation Phase Secondary users wishing to transmit data need to compete for the use of the CCC channel. The competition strategy employs a fixed window backoff mechanism called the FWSB algorithm. This algorithm sets different backoff time windows for each level of secondary user. First, a fixed window value w is set. Then, level-1 users' backoff time is randomly generated within [0, w-1], level-2 users' within [w, 2w-1], and level-3 users' within [2w, 3w-1]. By setting completely non-overlapping backoff windows for the three levels of secondary users, with higher-level users having smaller backoff windows, the algorithm ensures that high-level secondary users always access the CCC channel (common control channel) earlier, while low-level users basically cannot obtain CCC usage rights before high-level users. Additionally, this protocol stipulates that all secondary users prioritize selecting from level-1 available channels for reservation, ensuring that level-1 available channels are always reserved by higher-level users first. When the number of high-level users is small, lower-level secondary users can also reserve level-1 channels, guaranteeing full utilization of level-1 channels.

This paper does not adopt the binary exponential backoff algorithm but instead stipulates that secondary users' backoff windows in each backoff stage are fixed and identical to those in the first backoff stage. For example, for a level-1 user, when its backoff timer reaches 0 and it begins data transmission but a collision occurs and transmission fails, it enters the second backoff stage to restart random backoff. However, its backoff timer value is still randomly selected from [0, w-1]. If another collision occurs after the timer reaches 0, the value is again randomly selected from [0, w-1]. Similarly, level-2 users always have a backoff window of [w, 2w-1], and level-3 users always have [2w, 3w-1]. Regarding the binary exponential backoff algorithm, reference [**?**] points out that 802.11 networks exhibit unsatisfactory fairness due to the binary exponential backoff algorithm, and reference [**?**] also mentions that users with different contention window sizes (such as (0,7) and (0,15)) have different probabilities of accessing the channel, leading to poor fairness among users. Therefore, from a fairness guarantee perspective, the classic binary exponential backoff algorithm is not suitable. On the other hand, fixed window backoff strictly ensures that the backoff windows of different-level secondary users are non-overlapping at any time, with higher-level users' backoff windows strictly smaller than those of lower-level users. This provides good differentiation among the three types of secondary users, ensuring that high-level secondary users always obtain CCC usage rights before low-level users and consequently reserve level-1 channels first.

To reduce the increased collision probability caused by abandoning the binary exponential backoff algorithm, the value of w can be set slightly larger, which correspondingly reduces the probability that different secondary users select the same backoff time.

1.3 Data Transmission

After the contention phase ends, all node pairs that have completed channel reservation begin sending data independently and in parallel on their respective channels. Since high-level users typically reserve level-1 channels, the data transmission phase is usually contention-free, effectively improving channel utilization. Low-level users typically reserve level-2 channels, so their data transmission phase is usually competitive. The competitive access strategy in the data transmission phase uses the CSMA/CA technology from the 802.11 network DCF mechanism. Whether secondary user data transmission is contention-free or competitive fundamentally depends on whether the reserved channel is level-1 or level-2. If it is a level-1 channel, data transmission is contention-free; otherwise, it is competitive. Additionally, if some node pairs have not completed channel reservation during the negotiation phase, they must wait until the next beacon period to compete for the CCC channel again with all nodes.

After the data transmission phase ends, all nodes clear their NAV vectors and enter the next beacon period, beginning again with the sensing phase to sense channels.

2 FQMAC Protocol Modeling and Analysis

As described in Section 1.1, each beacon period is divided into three phases: sensing phase, channel negotiation phase, and data transmission phase. For the sensing phase, since this phase stipulates that all nodes cannot perform data transmission and all nodes remain synchronized to conduct spectrum sensing uniformly, and sensing efficiency is related to hardware performance (current cognitive radio node hardware performance is insufficient to sense all spectrum bands within limited sensing time, only partial spectrum can be sensed, and the selection of sensing bands is another research area; this paper assumes cognitive nodes can sense all bands and does not elaborate on partial sensing), and is less affected by other factors, the duration of the sensing phase can be fixed as a determined value. Similarly, the duration of the data transmission phase is mainly related to users' own traffic data volume and fixed channel transmission rates and can also be fixed. Based on these reasons, this paper only discusses the meaningful duration of the second phase.

This paper assumes there are n nodes in a network domain, including n1 level-1 users, n2 level-2 users, and n3 level-3 users. It is assumed that each node immediately has another frame to send after a successful transmission. Let f(t) represent the backoff window size of a node at time slot t. Additionally, a special random process g(t) is defined to represent the backoff stage of a node at time t. Obviously, the backoff stage value is always 0. In this case, the random process {g(t), f(t)} is a discrete-time Markov chain.

2.1 Markov Chain Model The state transition diagrams for level-1, level-2, and level-3 users are shown in Figures 2 [Figure 2: see original paper], 3 [Figure 3: see original paper], and 4 [Figure 4: see original paper] respectively.

Obviously, the backoff stage of a node in any state is 0. Let s represent the actual current backoff window size of a node in a certain state. Then the state {0, s} can represent all states in the figures. Additionally, let pc represent the probability of frame transmission collision, and po represent the probability that the channel is busy.

The transition probabilities between states are as follows:

a) When a station senses the channel is idle, the backoff timer decreases by 1, and the probability of state transition is $1 - p_o$.

b) When a station detects the channel is busy, the probability of freezing the backoff timer is p_o.

c) According to CSMA/CA mechanism regulations, when a station' s transmission fails, it must retransmit and re-execute CSMA/CA. This paper adopts this regulation, and the probability of transmission failure is p_c (independent of channel state because when the backoff timer is 0, the channel must be idle). Therefore, the probability of a level-1 station transitioning from state {0,0} to a certain state {0,s} (where $0 \leq s \leq w-1$) is p_c/w. Similarly, the probability of a level-2 node transitioning to a certain state {0,s} (where $w \leq s \leq 2w-1$) is also p_c/w, and the probability of a level-3 node transitioning to a certain state {0,s} (where $2w \leq s \leq 3w-1$) is also p_c/w.

According to CSMA/CA mechanism regulations, after a successful transmission, sending a second frame also requires re-executing CSMA/CA. However, in this paper, after obtaining CCC usage rights through the backoff algorithm, the purpose is achieved as long as one successful transmission reserves a channel; there will be no second transmission. Therefore, state transition probabilities after successful transmission are not considered here. Thus, for all three levels of secondary users, the probability of transitioning from state {0,0} to state {0,s} is p_c/w.

According to reference [**?**], let $b_{0,s} = \lim_{t\to\infty} P\{g(t) = 0, f(t) = s\}$ be the stationary distribution of the Markov chain. Based on Markov chain theory and conclusions from [**?**], the following equations hold in steady state:

For level-1 nodes:

$$b_{0,0} = \frac{2}{w+1}$$

Similarly for level-2 nodes:

$$b_{0,0} = \frac{2}{2w+1}$$

And for level-3 nodes:

$$b_{0,0} = \frac{2}{3w+1}$$

Additionally, according to probability conservation laws:

$$\sum_{s=0}^{w-1} b_{0,s} = 1$$

2.2 Channel Negotiation Phase Duration Analysis When the CCC channel is idle, this paper divides time into multiple slots with slot length e. Let represent the probability that a station begins transmitting information in a slot. Since a station starts transmitting data when its backoff timer equals 0, which corresponds to the station being in state {0,0} in this Markov chain model, can be expressed as:

For the three levels of secondary users, the values are:

$$\mu_1 = \frac{2}{w+1}, \quad \mu_2 = \frac{2}{2w+1}, \quad \mu_3 = \frac{2}{3w+1}$$

The probability that the channel is busy in a slot (assuming primary users are not using the channel), i.e., the probability that at least one of the n secondary user nodes transmits data, can be expressed by equation (7):

$$p_o = 1 - (1-\mu_1)^{n_1}(1-\mu_2)^{n_2}(1-\mu_3)^{n_3}$$

Under the condition that at least one station transmits data (i.e., p_o), the probability of a successful transmission is the probability that only one station transmits on the channel. Let p_m represent the probability that only one station successfully transmits in a slot, then p_m is given by equation (8):

$$p_m = n_1\mu_1(1-\mu_1)^{n_1-1}(1-\mu_2)^{n_2}(1-\mu_3)^{n_3} + n_2\mu_2(1-\mu_2)^{n_2-1}(1-\mu_1)^{n_1}(1-\mu_3)^{n_3} + n_3\mu_3(1-\mu_3)^{n_3-1}(1-\mu_1)^{n_1}(1-$$

In the CCC channel contention phase, let p_n represent the probability that the channel is idle in a slot, p_u represent the probability of successfully completing an information exchange in a slot, and p_d represent the probability of failing to complete an information exchange. Then:

$$p_n = 1 - p_o, \quad p_u = p_o \cdot p_m, \quad p_d = p_o \cdot (1 - p_m)$$

The average time to successfully reserve a channel in the CCC channel contention phase, denoted as , is:

$$\eta = \frac{p_u t_u + p_d t_d + p_n e}{p_u}$$

where t_u is the average time a successful information exchange occupies the channel, t_d is the average time the channel is in collision state, and e is the slot length. Specifically:

$$t_u = \text{RTS} + \text{SIFS} + \text{CTS} + \text{SIFS} + \text{CRTS} + \sigma$$

$$t_d = \text{RTS} + \text{DIFS}$$

where is the propagation delay.

If an RTS transmission fails, the channel becomes idle again after a DIFS (Distributed Inter-Frame Spacing) time.

Assuming the competition for CCC channel phase (channel negotiation and reservation phase) has duration T, the reasonable duration of the channel negotiation and reservation phase can be derived from the above conclusions. The duration equals the average time to reserve a channel, , multiplied by the number of available channels in the current CRN. If the current CRN has n_{ch} available channels, the duration of the channel negotiation and reservation phase that can guarantee successful reservation of all available channels can be approximated as:

$$T = n_{ch} \cdot \eta$$

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3 Experimental Simulation

This paper considers a network model where all secondary user nodes in a cognitive radio network A are uniformly distributed in the network domain. There are 3 level-1 secondary users and 2 level-3 secondary users in this network domain. Meanwhile, there is a coexisting heterogeneous cognitive radio network B with 2 secondary users. There are 5 fixed available licensed channels in the current area, with primary user arrival probability p_u. It is assumed that the 2 secondary users in network B have already occupied 2 licensed channels before the secondary users in network A begin communication. For simulation convenience, this paper assumes that secondary users can sense all licensed channels during the sensing phase (typically, secondary users can only sense partial channels in a short time; the issue of partial sensing is not elaborated here). It is also stipulated that each secondary user that has reserved a channel has 5 consecutive frames to send during the data transmission phase, with frame size of 256 bytes. Under these settings, simulation experiments were conducted using the OMNeT++ simulation tool.

This paper compares FQMAC with OMC-MAC [**?**] (which also uses a common control channel) and ACAP-MAC [**?**]. Figure 5 [Figure 5: see original paper] shows the simulation comparison results (the vertical axis shows normalized results). Clearly, the throughput performance of FQMAC is significantly better than that of OMC-MAC and ACAP-MAC. As the arrival probability of PU (primary users) gradually increases, the availability of licensed channels gradually decreases, and the throughput of all three communication protocols decreases accordingly. However, it is evident that regardless of channel availability, FQMAC' s throughput is better than the other two MAC protocols. This is mainly because FQMAC makes channels occupied by secondary users from other heterogeneous networks available through competition, which could not be used in OMC-MAC and ACAP-MAC. Although data transmission using these channels is competitive, it still increases the number of available channels. The simulation results in Figure 5 visually demonstrate this effect.

Similarly, this paper considers the same experimental background with 2 heterogeneous network secondary users occupying 2 licensed channels to conduct this experiment. A comparison between OMC-MAC and FQMAC is performed (OMC-MAC is also a MAC protocol that considers QoS requirements). The simulation results are shown in Figure 6 [Figure 6: see original paper], where the vertical axis values are normalized.

The results show that the average delay of QoS users (level-1 users in FQMAC) under OMC-MAC and FQMAC is similar. However, there is a significant gap for ordinary users. The delay of ordinary users under OMC-MAC is much higher than that under FQMAC, and the delay variation of ordinary users under OMC-MAC is small. This is mainly because under OMC-MAC, all users can only sense 3 idle channels. When QoS users exist, the 2 ordinary secondary users basically have to wait until QoS users are not using the channels to access them. If QoS users continuously have data to transmit, they will seize the channel every beacon period, causing ordinary secondary users to wait indefinitely or even be "starved." Under FQMAC, the 2 ordinary users can compete with secondary users from heterogeneous networks for channel usage, resulting in significantly better average access delay than OMC-MAC. For ordinary users and high-level QoS users under the same protocol, the average access delay of QoS users is significantly better than that of ordinary users, indicating that both protocols satisfactorily meet the needs of QoS users. However, FQMAC performs better than OMC-MAC in terms of average delay for ordinary users while meeting QoS user requirements.

To test the fairness of the FQMAC protocol, this paper introduces the Jain Index mentioned in [**?**]. Assume there are N coexisting CRNs. Let Δ represent a small time period called a cycle. Record the transmission time of each CRN in the previous K cycles, and let vector $T(k) = [T_1(k), T_2(k), ..., T_N(k)]$ represent the transmission time of each CRN in the previous k cycles (kΔ). Under these conditions, the Jain Index can be expressed as:

$$J(T(k)) = \frac{(\sum_{i=1}^{N} T_i(k))^2}{N \sum_{i=1}^{N} T_i(k)^2}$$

where $T(k)$ is a row vector of 1 row and N columns, and its transpose matrix $T(k)^T$ is a column vector of N rows and 1 column. The Jain Index can be calculated based on the recorded transmission time and N. A larger Jain Index indicates better fairness. In the ideal case, the Jain Index is 1. In this paper, Δ is set as the time required to continuously send 5 frames. Tests are conducted with N values of 5 and 10 (i.e., scenarios with 5 coexisting CRNs and 10 coexisting CRNs), and the simulation results are shown in Figure 7 [Figure 7: see original paper].

Figure 7 shows that under the same number of coexisting CRNs, the fairness index of FQMAC is significantly higher than that of OMC-MAC, indicating that FQMAC's fairness is better than OMC-MAC's. This is mainly because FQMAC enables secondary users in the current network to compete with secondary users from heterogeneous networks for channel usage. The figure also shows that when the number of CRNs increases, the fairness of OMC-MAC decreases significantly, indicating that the number of coexisting CRNs has a greater impact on fairness, and the more coexisting CRNs there are, the worse the fairness. However, relatively speaking, as the number of CRNs increases, the fairness index of

FQMAC does not decrease significantly, indicating that FQMAC performs well in terms of fairness even when the number of coexisting CRNs changes.

4 Conclusion

This paper proposes a MAC protocol called FQMAC for cognitive radio networks considering the coexistence of heterogeneous networks. This protocol ensures maximum availability of channels in heterogeneous network coexistence scenarios, enabling secondary users to use more channels for transmission. Building upon this, channel classification and secondary user classification mechanisms are proposed, along with a QoS guarantee mechanism based on these classifications. Available channels are classified according to their characteristics, making secondary user channel selection more reasonable and guaranteeing the needs of secondary users with high QoS requirements. Simultaneously, all users reserve channels in descending order of priority, ensuring priority utilization of high-quality channels, making channel resource utilization more efficient, and further optimizing network performance. Theoretical analysis through a Markov chain model yields the theoretical value of the reasonable duration for the channel negotiation and reservation phase. Simulation experiments show that under the same background, FQMAC achieves significantly improved network throughput compared to reference MAC protocols. Additionally, FQMAC provides better improvement in channel access delay for ordinary users compared to reference protocols. By adopting the three-state channel model, secondary users can compete with secondary users from heterogeneous networks for licensed channel usage, which also improves fairness among secondary users in the network. Furthermore, the control information exchange mechanism (RTS-CTS mechanism) adopted in this paper avoids hidden terminal problems and reduces the probability of conflicts between secondary users and primary users caused by sensing errors. Moreover, the transmission of high-level secondary users in the data transmission phase is usually contention-free, which effectively improves the utilization of spectrum holes.

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Note: Figure translations are in progress. See original paper for figures.