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On-demand ecology-inspired spectrum allocation mechanism for heterogeneous cognitive radio networks

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Abstract As increasing number of cognitive radio network (CRN) standards are developed in TV White Spaces band with incompatible communication patterns, heterogeneous CRNs coexistence problem could not be avoided. However, most solutions on this problem have not considered CRNs' actual data transmission demands and weighted fairness simultaneously. Therefore, we would like to introduce a novel *On-demand ecological Species Competition based HEterogeneous networks coexistence MEchanism* (*O-SCHEME*) in this paper. Inspired by ecology species competition model, *O-SCHEME* utilizes an ecology based spectrum allocation mechanism for guaranteeing heterogeneous CRNs' spectrum shares weighted fairness. And by employing CRNs' communication spectrum requirement constraints, actual data transmission needs could be satisfied without wasted communication resources. Through both theoretical and simulation analyses, we demonstrate that *O-SCHEME* can achieve stable and fair spectrum allocations among coexisting networks with high communication efficiency.

Keywords Cognitive radio networks · Ecology based algorithm · Networks coexistence · Weighted fairness · Communication resources demands

1 Introduction

In the past decades, ubiquitous utilizations of wireless networks devices have lead rare available spectrum resources can be authorized. However, most spectrum bands have not been utilized adequately by licensed wireless networks. In the report of *Federal communication commission* (FCC) [1], many licensed spectrum bands are only employed in some limited geographical areas or specific time periods, and average utilizations of these bands vary from 15 to 85%.

Consequently, as a promising technology, *cognitive radio network* (CRN) technology has been presented for reutilizing these insufficient spectrum resources [2,3]. On the other side, because massive transformation from TV analog broadcasting signals to digital pattern, original TV spectrum bands (e.g. VHF/UHF 54–698 MHz) have been redefined as "*TV white spaces*" (TVWSs) for new CRN standards testing [4]. In this case, a number of emerging CRN standards are proposed to operate on TVWSs, e.g. IEEE 802.22 Wireless regional area networks (WRAN) [5], IEEE 802.11af (WiFi over TVWS) [6], IEEE 802.16h [7] and ECMA 392 (WPAN over TVWS) [8] etc.

However, incompatibility between heterogeneous CRNs gives challenges on CRNs' data transmission, contention of spectrum bands could not be avoided [9]. Considering this situation, existing CRN standards have prepared wireless networks coexistence mechanisms to harmonize CRNs

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communication, but most of them focus on homogeneous networks' coexistence [10].

In order to coordinate heterogeneous CRNs, IEEE 802.19.1 task force presents a novel mediator system IEEE 802.19.1 standard [11]. By equipping this system, heterogeneous CRNs' information could be connected together. Whereas, no coexistence mechanism is embedded on the IEEE 802.19.1 system.

Therefore, Bian et al. proposes "*Symbiotic Heterogeneous coexistence ARchitectuRE*" (SHARE) coexistence framework on IEEE 802.19.1 system [12,13]. By employing the *Lotka–Volterra* (L–V) *predator-prey* model, a novel weighted fair spectrum allocation mechanism is provided. But unappropriate spectrum sharing model causes suboptimal results, CRNs' competitions have not been harmonized completely. So, we and Yin et al. have proposed 2 different improvements on SHARE in [14,15] to allocate spectrum bands fairly.

Nevertheless, this type of solutions concentrates more on heterogeneous CRNs' spectrum allocations' weighted fairness than actual data transmission demands, redundant spectrum resources may be occupied without utilization when assignable spectrum bandwidths are larger than CRNs' requirements. Thus, communication resources would be wasted by allocating over-saturated spectrum bandwidths to candidate CRNs with these solutions. What is more, unnecessary reduction of communication efficiency would be generated when new CRNs access into TVWSs for scrambling these redundant spectrum bands.

In order to counterbalance weighted fairness and actual data transmission demands of heterogeneous CRNs, a novel "*On-demand ecology Species Competition based HEterogeneous networks coexistence MEchanism*" (O-SCHEME) would be provided in this paper. As the name "*O-SCHEME*" indicates, this approach is a modified generation of [14], so *O-SCHEME* could allocate spectrum bands fairly through ecology based spectrum competition model with indirect mediator system, and CRN's data transmission demands would be taken into account. Via a series of simulations and comparisons, *O-SCHEME* could successfully allocate spectrum bands into fair shares with consideration of data transmission demands, and have more brilliant performances on overall throughput. The major contributions of this paper from [14] could be summarized as follows:

- With the consideration of CRNs' data transmission demands, a more precise evaluation criterion on heterogeneous spectrum sharing could be provided. Therefore, unnecessary communication resources waste could be avoided.
- By utilizing on-demand ecology based spectrum competition model, heterogeneous CRNs have more selectivity on spectrum bandwidths, which fits practical scenario better.
- The novel competition spectrum constraint gives minimized cost for new CRNs accessing in local coexistence environment.
- More theoretical analyses and comparisons provide proofs on superiority and reliability of *O-SCHEME*.

For the rest of this paper, Sect. 2 would introduce the related work. A comprehensive technical background introduction would be held in Sect. 3. Section 4 would present *O-SCHEME* in details and analyze in different aspects. While multiple comparisons simulations would be evaluated in Sect. 5, and conclusion would be stated in Sect. 6.

2 Related work

In this section, related works would be reviewed in 2 different aspects.

2.1 Homogeneous coexistence

As introduced in Sect. 1, most existing CRN standards have provided homogeneous CRNs coexistence mechanisms.

- **IEEE** 802.22: A 2-mode homogeneous coexistence mechanism is prepared in IEEE 802.22 [5]. For IEEE 802.22 networks, spectrum utilization schedules of neighbor networks are coordinated through their Base Stations, while for different "cells" in the same network, communications are harmonized by a meticulous mechanism.
- **IEEE** 802.16*h*: In IEEE 802.16*h* [7], coexistence information could be exchanged through specific control channel, and homogeneous CRNs coexistence is realized by 2-degree data transmission schedule mechanism (uncoordinate and coordinate styles).
- **ECMA** 392: ECMA 392 network offers a *Beacon period* (BP) mechanism to compromise intra network frames collision, and deploys 3 different types of counter schemes to cope with corresponding homogeneous networks coexistence scenarios [8].

In general, homogeneous CRNs' collision could be harmonized by existing CRN standards, appropriate approaches for coordinating heterogeneous CRNs are still needed.

2.2 Heterogeneous coexistence

In this circumstance, a lot of heterogeneous networks coexistence mechanisms are proposed, which could be summarized as follows:

- **Autonomous schemes** In [16,17], Zhao et al. have presented a *fairness-oriented media access control* (FMAC) protocol. By developing new 3-state signal diagnosis model and cooperative primary users' location sensing mechanism, both collisions in heterogeneous Secondary Users networks and between Primary users and Secondary users networks could be mitigated. While Sun et al. have proposed a novel spectrum sharing mechanism for heterogeneous CR wireless sensor networks in [18]. *Stackelberg game theory* is utilized to harmonize spectrum sharing and data rate in Primary users and Secondary users networks for improving victim nodes' overall throughput. Similarly, Amjad et al. [19] have provided a game theory based coexistence mechanism. Through game theory, split data could be allocated into appropriate channels to minimize heterogeneous CRNs' data collision. In [20], Bian et al. have developed a novel coexistence protocol called "*Spectrum Sharing for Heterogeneous Coexistence*" (SHARE). *Beacon transmission* and *Quiet period* mechanisms are employed to coordinate heterogeneous CRNs' data transmission shares in time dimension, hence, heterogeneous CRNs' communications could be harmonized.
- **Centralized schemes** This type of schemes employs IEEE 802.19.1 as mediator system, so heterogeneous CRNs could be coordinated in a centralized way. Bian *et al.* have presented a "*Symbiotic Heterogeneous coexistence ARchitectuRE*" (SHARE) coexistence framework with IEEE 802.19.1 mediator in [12,13]. Spectrum shares of heterogeneous CRNs are allocated fairly through ecology based spectrum competition model. However, the novel ecology based spectrum competition model has some faults, which causes sub-optimal results of spectrum allocations. To correct this error, [14,15] have proposed 2 different solutions to share spectrum bands fairly. In [14], we have proposed the "*ecology Species Competition based HEterogeneous networks coexistence MEchanism*" (SCHEME) as preliminary work of this paper. By optimizing the spectrum competition model, fair spectrum shares and optimal outcomes could be acquired. While in [15], Yin et al. have introduced L–V-based nonlinear feedback control system (NFCS) into spectrum sharing allocation algorithm, which extends the value range of competition coefficient in L–V model, and gives us a new idea on spectrum sharing.
- **Other schemes** Besides, there also exist some heterogeneous networks coexistence mechanisms in other spectrum bands which could give us inspiration. For cellular networks, a novel networks architecture is presented for eliminating interferences from 4G cellular networks to WiFi when they share the same unlicensed 2.4 or 5 GHz spectrum bands [21]. A cooperative Nash bargaining resource allocation algorithm is introduced to solve the joint subchannel and power allocation problem in cognitive small cell networks with the consideration of intra-small cell networks fairness and imperfect Channel state information [22]. While for WiFi and ZigBee coexistence, MIMO system is employed to alleviate WiFi interference in ZigBee data [23,24]. Ant Colony based optimization [25], QoS based resource allocation algorithm [26] and other solutions [27] have also presented new ideas for femtocells networks coexistence.

3 Technical background

3.1 Motivation

As stated previously, although weighted fairness has been realized by some heterogeneous CRNs coexistence mechanisms, actual demands of data transmission are still considered rarely.

But why should we consider these two points simultaneously in coexistence between heterogeneous CRNs?

Firstly, weighted fairness is an important parameter for heterogeneous CRNs, which could measure spectrum resources allocation balance of CRNs, and maximize overall communication efficiency of heterogeneous CRNs. So it should be in the consideration of coexistence mechanism.

On the other hand, as a scalar value for counting data transmission amounts and speeds, data transmission demand could quantize practical communication resources requirements of each CRN indirectly, which is fundamental element for weighted fairness spectrum sharing. Thus, it is qualified to be taken into account in coexistence mechanism.

Meanwhile, weighted fairness is guaranteed by coexistence mechanisms (e.g. [12–15] etc.), but outputs of data transmission are not always perfect, especially in some special scenarios.

As shown in Fig. 1, "true scenario" indexes actual demands of 2 different CRNs, "*SHARE-Time*" represents *SHARE* in [20], "*SHARE-Spectrum*" indicates *SHARE* in [12, 13], "*SCHEME*"which would also be utilized to describe corresponding coexistence mechanisms in [14].

Suppose τ is the total transmission time, $\mathcal{A}$ is the total spectrum bandwidth, P is the amount of data packets waiting for transmission, and λ is the coefficient between bandwidth and data transmission speed. There should exist,

$$P = \lambda \mathcal{A} \tau.$$

So, if $CRN1$ should send P_1 packets, and $CRN2$ should send P_2 packets. The actual packets which are transmitted in the 4 different scenarios could be depicted as,

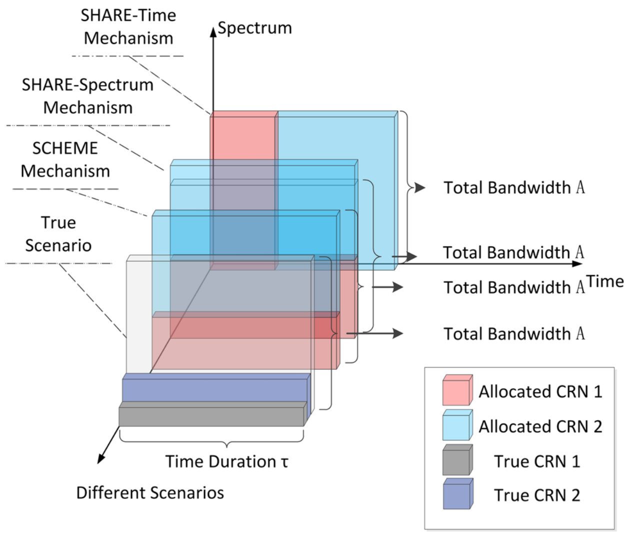

Fig. 1 Fairness coexistence performance between 3 mechanisms

$$\begin{cases} P_1' = P_1, & P_2' = P_2. & \text{True} \\ P_1' = \frac{\mathcal{A}\lambda_1\lambda_2 P_1\tau}{\lambda_2 P_1+\lambda_1 P_2}, & P_2' = \frac{\mathcal{A}\lambda_1\lambda_2 P_2\tau}{\lambda_2 P_1+\lambda_1 P_2}. & \textit{SHARE-Time} \\ P_1' = \frac{\mathcal{A}\lambda_1\lambda_2 P_1\tau}{\lambda_2 P_1+\lambda_1 P_2}, & P_2' = \frac{\mathcal{A}\lambda_1\lambda_2 P_2\tau}{\lambda_2 P_1+\lambda_1 P_2}. & \textit{SCHEME} \\ P_1' \le \frac{\mathcal{A}\lambda_1\lambda_2 P_1\tau}{\lambda_2 P_1+\lambda_1 P_2}, & P_2' \le \frac{\mathcal{A}\lambda_1\lambda_2 P_2\tau}{\lambda_2 P_1+\lambda_1 P_2}. & \textit{SHARE-Spectrum} \end{cases}$$

where P_1' and P_2' represent real transmission data packets amounts in different CRNs.

Therefore, we could find out that the transmitted data amounts have strong relation with the utilized communication resources if CRNs spectrum shares allocations are weighted fairness and speed coefficients are the same (e.g. *SHARE-Time* and *SCHEME*). But the weighted fairness mechanism could not always guarantee performance (e.g. *SHARE-Spectrum*).

For another, the final results of CRNs' communication would not change until $\mathcal{A}$ change if ratios between CRNs' data transmission demands keep the same, even their demands decrease. Which may cause lower communication efficiency. Take *SCHEME* as example, suppose R_i is spectrum bandwidth requirement. Then, we could get that

$$R_1 = \frac{P_1}{\lambda_1\tau}, \quad R_2 = \frac{P_2}{\lambda_2\tau},$$

And the actual spectrum bandwidth allocated to CRNs is represented by S_i,

$$S_1 + S_2 = \mathcal{A},$$
$$S_1 = \frac{R_1}{R_1+R_2}\mathcal{A}, \quad S_2 = \frac{R_2}{R_1+R_2}\mathcal{A}.$$

Therefore, if $\frac{R_1}{R_2}$ keeps the same, and P_is decrease to small enough, there would be $R_1 + R_2 < \mathcal{A}$, and

$$S_1 > R_1, S_2 > R_2. \Rightarrow$$
$$P_1' = \lambda_1 S_1\tau = \frac{\lambda_1\mathcal{A}\tau}{1+\frac{R_2}{R_1}} > P_1 = \lambda_1 R_1\tau,$$
$$P_2' = \lambda_2 S_2\tau = \frac{\lambda_2\mathcal{A}\tau}{1+\frac{R_1}{R_2}} > P_2 = \lambda_2 R_2\tau.$$

Consequently, the more data transmission demands decrease, the more spectrum resources would be allocated as unused statuses. And long term of coordination time would be cost when new CRNs access in and compete for these unused spectrum. Which is unnecessary communication resources waste under weighted fairness statements. Correspondingly, in *SHARE-Time* and *SHARE-Spectrum* scenarios, there also exist this phenomenon.

Hence, weighted fairness should not be the only measurement of spectrum sharing in heterogeneous CRNs coexistence, and the actual data transmission demands must be taken into consideration.

3.2 Problem definition

Therefore, in order to optimize coexistence mechanism with consideration of actual data transmission demands, objective problem of spectrum shares allocation should be reproposed appropriately.

Let $\mathcal{L}$ index the set of n CRNs which coexist in a limited space with $\mathcal{A}$ channels for communication, and the data packets amounts which these CRNs need to transmit are denoted as $P_{R1}, P_{R2}, \ldots, P_{Rn}$. So that, a packets requirements vector could be defined as following,

$$\boldsymbol{P_R}(\mathcal{L}) = [P_{R1}, P_{R2}, \ldots, P_{Rn}].$$

On the other hand, the set of CRNs' spectrum bandwidth shares which could be sensed and controlled directly are represented as $S_1, S_2, \ldots, S_n$, the allocated spectrum shares vector could be indicated as

$$\boldsymbol{S}(\mathcal{L}) = [S_1, S_2, \ldots, S_n].$$

Therefore, suppose λ denotes the speed coefficient, in τ period, the transmitted data amount of CRN i could be calculated as

$$P_i = \int_0^{\tau} \lambda_i S_i(t)dt. \tag{1}$$

Then, for the purpose of evaluating actual communication resources which are utilized on data transmission, a new coefficient '*communication efficiency*' would be introduced. By accumulating differences between data transmission demands and actual packets amounts which are transmitted on allocated spectrum bands, a concrete value is employed,

$$P_\epsilon = \begin{cases} \sum_{i=1}^{n} |P_i - P_{Ri}|, & \sum R < \mathcal{A}. \\ \sum_{i=1}^{n} |P_i - \lambda_i \frac{R_i}{\sum R} \mathcal{A}\tau|, & \sum R \geqslant \mathcal{A}. \end{cases} \tag{2}$$

where P_ϵ represents the difference value, and $\lambda_i \frac{R_i}{\sum R} \mathcal{A}\tau$ indicates maximum packets amounts could be send under available spectrum bandwidth.

Via normalization, the *communication efficiency* could be defined out as $F(\boldsymbol{S}(\mathcal{L}))$.

$$F(\boldsymbol{S}(\mathcal{L})) = 1 - \frac{P_\epsilon}{P_{\mathcal{A}}} = 1 - \frac{P_\epsilon}{\sum_{i=1}^{n} \lambda_i \frac{R_i}{\sum R} \mathcal{A}\tau}. \tag{3}$$

Where $P_{\mathcal{A}}$ represents maximized required packets throughput of overall spectrum bandwidth. Maximum value of $F(\boldsymbol{S}(\mathcal{L}))$ is one (the best case), and the worst value is zero where all packets transmission has been missed.

Besides, the weighted fairness is necessary, which could be guaranteed as $\frac{S_i}{S_j} = \frac{R_i}{R_j}$, where i and j represent different CRNs. The *on-demand data transmission problem* could be formulated as follows:

Problem 1 *Given a set of n coexisted CRNs, $\mathcal{L}$, with $\mathcal{A}$ spectrum channels, the problem has to be solved could be formulated as follows:*

$$\begin{aligned} &\textit{Maximize} \;\; F(\boldsymbol{S}(\mathcal{L})) \\ &\textit{Subject to} \;\; \frac{S_i}{S_j} = \frac{R_i}{R_j}. \end{aligned}$$

4 On-demand spectrum share allocation algorithm

For settling Problem 1, The On-demand spectrum share allocation algorithm is proposed. Then, a detailed introduction of this algorithm would be stated in this section.

4.1 Mediator sstem

In order to construct this on-demand algorithm which could sense and adjust heterogeneous CRNs' spectrum shares in real-time and maintain weighted fairness without communication resources wasted, four questions should be settled.

(1) **Cross-networks communication tunnels**
As the algorithm is proposed to harmonize heterogeneous CRNs, there may not exist effective communication approach through these heterogeneous networks, a cross-networks communication system which could be applied on different CRNs and supporting indirect negotiation is necessary.

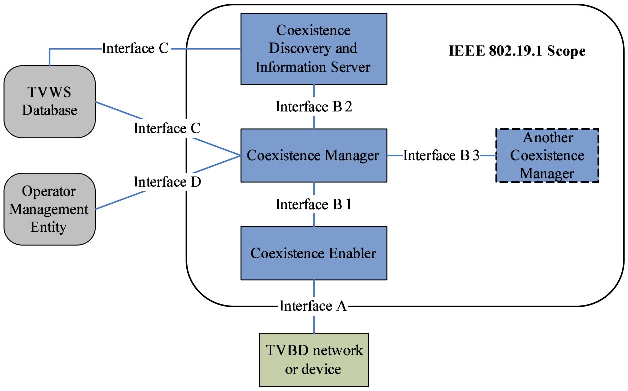

Fig. 2 IEEE 802.19.1 system architecture

(2) **High-efficient storage center**
Because multiple heterogeneous CRNs would operate on TVWSs, distributed type information exchanging mode through CRNs is not appropriate and efficient. So, a high-efficient storage center should be employed for spectrum messages.

(3) **Realtime spectrum information acquisition**
Since real-time sensed spectrum information of heterogeneous CRNs is very important for spectrum allocation, a real-time spectrum sensing and interacting mechanism is required.

(4) **QoS requirements exchange**
For the weighted fairness and *communication efficiency* calculation between heterogeneous CRNs, QoS requirements (data transmission demands in different time durations) are significant. Then, a QoS requirements exchange mechanism through heterogeneous CRNs is necessary.

Hence, to address these questions, a mediator protocol IEEE 802.19.1 which is proposed for TVWSs is employed in this paper to support the on-demand algorithm development.

As shown in Fig. 2, IEEE 802.19.1 could be divided into 3 separated parts in blue boxes: (1) *coexistence manager* (CM) is local decision maker for coexistence; (2) *coexistence database and information server* (CDIS) provides a comprehensive information interactive center to support CMs; and (3) *coexistence enabler* (CE) enables communications between CRNs' devices and IEEE 802.19.1 system. TVWS database mainly indicates the list of occupied channels and primary users' locations, and backhaul connections are equipped from TVWS database to 802.19.1 system.

Then, for these four questions, CE module could be employed for constructing cross-networks tunnels and providing valid data transmission way for real-time spectrum information and QoS requirements. And high-efficient storage and additional simple process capability could be supplied by CDIS. But CM module of IEEE 802.19.1 has not been utilized in this paper since centralized system is not necessary for the on-demand spectrum allocation.

On the other hand, real-time spectrum information and QoS requirements are both acquired by CRNs themselves. Hence, by utilizing base stations (BS) or some special terminals in CRNs which equip CEs, these information could be interacted with IEEE 802.19.1 mediator. So that, the four questions could be settled.

4.2 On-demand spectrum competition model

Through IEEE 802.19.1 mediator system, technical support on the spectrum allocation algorithm has been established. Combining the consideration of weighted fairness and data transmission demands of heterogeneous CRNs, an on-demand ecology based spectrum competition model which is inspired from corresponding model in [14] would be proposed in this part.

As we stated previously, this spectrum competition model is derived from *Lotka–Volterra* (L–V) *predator-prey* equation [28], which is the basic theory on population competition of different ecology species. In *L–V* model, multiple different ecology species groups' compete for limited nourishments as following:

$$\frac{dN_i}{dt} = r_i N_i \left(1 - \frac{N_i + \sum_{j \neq i} \alpha_{i,j} N_j}{K_i}\right). \tag{4}$$

where N_i represents the population size of predator, and K_i is the maximized population size under limited nourishments. While $\alpha_{i,j}$ indicates mutual impacts between specie i and j, r_i indexes intrinsic rate of increase.

4.2.1 Spectrum competition model

For spectrum competition in TVWSs, predator species is similar to heterogeneous CRNs, and limited nourishments could be transferred to limited spectrum resources, so the spectrum competition model could be depicted as following:

$$\frac{dS_i}{dt} = r S_i \left(1 - \frac{S_i + \sum_{j \neq i} \alpha_{i,j} S_j}{\rho C}\right). \tag{5}$$

In Eq. 5, S_i indexes ith CRN's spectrum share, C is the competition spectrum constraint, r is intrinsic rate which is the same for heterogeneous CRNs since spectrum competition has no essential distinction in different CRNs, ρ is an added QoS constraint, and $\alpha_{i,j}$ represents mutual interference.

4.2.2 Competition spectrum constraint

As stated above, different spectrum bandwidth requirements could have huge impacts on communication resources utilizations. Then, for different needs of spectrum bandwidth, suppose $\mathcal{L}$ represents the set of n coexistence CRNs, the competition spectrum constraint C could be divided into 2 types:

$$C = \begin{cases} \mathcal{A}, & \sum_{i \in \mathcal{L}} R_i > \mathcal{A}. \\ \sum_{i \in \mathcal{L}} R_i, & \sum_{i \in \mathcal{L}} R_i \leqslant \mathcal{A}. \end{cases}$$

When $\sum_{i \in \mathcal{L}} R_i$ is more than $\mathcal{A}$, the total spectrum bandwidth which could be utilized for heterogeneous CRNs is not enough, so bandwidth which S_is compete for could only be $\mathcal{A}$. Conversely, when $\sum_{i \in \mathcal{L}} R_i$ is less than $\mathcal{A}$, unused allocated communication resources would be generated by using $\mathcal{A}$ bandwidth for competition, so the competition spectrum constraint C would choose $\sum_{i \in \mathcal{L}} R_i$.

On the other side, in *SHARE-Spectrum* [12,13] and *SCHEME* [14], a precondition of allocated spectrum bandwidth has been supposed, which is that the allocated spectrum shares must be in the range $[0, \mathcal{A}]$.

However, this precondition has not been taken seriously, and it is not precise enough. When S_i is more than $\rho C(\frac{1}{r} + 1) - \sum_{j \neq i} \alpha_{i,j} S_j$, there would be:

$$\frac{dS_i}{dt} = r S_i \left(1 - \frac{S_i + \sum_{j \neq i} \alpha_{i,j} S_j}{\rho C}\right) < -S_i. \tag{6}$$

Then, the result of allocated spectrum in CRN ith would be calculated to be negative and decrease to $-\infty$, all other spectrum allocations S_j would also become divergent, so a precise definition of S_i's value range is needed. But no specific explanation about this field has been stated in the *SHARE-Spectrum*, while although a value range definition of S_i has been defined in problem definition of *SCHEME*, a clear spectrum value constraint in calculation has also not been mentioned.

Therefore, we would like to redefine the S_i's calculation constraint in this paper, which could be figured as following:

$$\forall S_i = \begin{cases} S_i, & S_i > 0. \\ \varepsilon, & S_i \leqslant 0. \end{cases}$$

When allocated spectrum bandwidth S_i is larger than 0, it would not be changed since which is appropriate for spectrum competition. Corresponding, when S_i is less than 0, a minimum positive value ε would be introduced to replace the original negative S_i, so the generation of spectrum competition divergent result would be prevented.

4.2.3 *QoS constraint*

Because ρ represents heterogeneous CRNs' needs of QoS, it should have tight relationship on CRNs' spectrum bandwidth requirements, then, the detailed formulation of ρ could be figured out as:

$$\rho = \frac{\sum_{i\in\mathcal{L}} R_i - (n-1)}{\sum_{i\in\mathcal{L}} R_i}.$$

For the competing CRNs, at least 1 spectrum channel should be required. So for each CRN, only $\sum_{i\in\mathcal{L}} R_i - (n-1)$ could be compete for as maximum spectrum bandwidth. Therefore, in the total spectrum bandwidth which heterogeneous CRNs allocate, the maximum 'prey' spectrum could be formulated as ρC.

4.2.4 *Mutual interference*

As the mutual interference coefficient, $\alpha_{i,j}$ represents the interference from CRN ith to CRN jth. However, as the spectrum interferences between heterogeneous CRNs have no essential differences, we could derive that the interference which CRN ith gives to CRN jth should be the same as interference which CRN ith gives to CRN $j+1$th. Then, for all coexistence heterogeneous networks, we could formulate that:

$$\alpha_{i,1} = \alpha_{i,2} = \cdots = \alpha_{i,n} = \alpha_i.$$

While because α_i has crucial impact on weighted fairness, α_i could be depicted as:

$$\alpha_i = 1 - \frac{1}{R_i} = \frac{R_i - 1}{R_i}.$$

4.3 Spectrum sharing algorithm

Through introduction above, the on-demand ecology based spectrum competition model could be defined as following:

$$\frac{dS_i}{dt} = rS_i\left(1 - \frac{S_i + \sum_{j\neq i}(1-\frac{1}{R_j})S_j}{\frac{\sum_{i\in\mathcal{L}} R_i-(n-1)}{\sum_{i\in\mathcal{L}} R_i}C}\right). \tag{7}$$

For simplifying collection and calculation in IEEE 802.19.1 mediator, a novel parameter η_i has been introduced to represent the competition part in Eq. 7:

$$\eta_i = \left(1 - \frac{1}{R_i}\right) S_i$$

so a sanitized parameter β_i could be formulated as:

$$\beta_i = \sum_{j\neq i} \eta_j.$$

From another aspect, suppose a ϕ could represent the competition spectrum constraint, there would exist

$$\phi = \frac{\sum_{i\in\mathcal{L}} R_i - (n-1)}{\sum_{i\in\mathcal{L}} R_i} C.$$

Therefore, Eq. 7 could be transformed to

$$\frac{dS_i}{dt} = rS_i\left(1 - \frac{S_i + \beta_i}{\phi}\right) \tag{8}$$

Then, based on the Eq. 8, the spectrum sharing algorithm could be figured out as Algorithm 1, and the detailed description could be presented as follows:

(i) At first, as an on-demand spectrum sharing algorithm, the real-time spectrum bandwidth requirement R_i must be gained.
(ii) Before iteration, mutual influence parameter β_i and overall QoS constraint ϕ should be updated from mediator.
(iii) If R_i changed, which means spectrum requirements of CRN i has been changed from state before, hence, R_i should be obtained again to guarantee S_i accuracy.
(iv) If $\frac{dS_i}{dt} \neq 0$, S_i is modified, and follow the pace of networks' competition.
(v) When S_i is less than 0, a minimum positive value ε would be assigned to S_i.
(vi) At the end of each iteration, network i needs to send influence coefficient $\eta_i = (1-\frac{1}{R_i})S_i$ and current required bandwidth R_i to mediator, meanwhile, sanitized data β_i and calculated ϕ would be downloaded for next iteration.
(vii) Last step is repeating iteration until no non-zero $\frac{dS_i}{dt}$ exists, that is $\frac{dS_i}{dt} = 0$ for every spectrum shares.

4.4 Analyses of stable equilibrium

After the algorithm presented previously, the on-demand ecology based spectrum competition system has been established, then, detailed analyses on this algorithm's equilibrium and stability would be provided.

4.4.1 *Weighted fairness*

At first, the fairness between allocated spectrum bandwidths of heterogeneous CRNs should be guaranteed.

Algorithm 1 Spectrum sharing alogrithm

```
Input: intrinsic rate $r$, $i$th network's spectrum requirement $R_i$, $i$th network's influence $\eta_i$, the sanitized data $\beta_i$, overall spectrum requirements constraints $\phi$.
Output: $i$th network's spectrum share $S_i$.
Collect current required spectrum bandwidth $R_i$.
Update $\beta_i$ and $\phi$ from IEEE 802.19.1 mediator.
while $\exists i \in \mathcal{L}, s.t. \frac{dS_i}{dt} \neq 0$ do
    if $R_i$ changed then
        collect new $R_i$
    end if
    if $\frac{dS_i}{dt} \neq 0$ then
        $S_i = S_i + \frac{dS_i}{dt}$
        if $S_i \leqslant 0$ then
            $S_i = \varepsilon$
        end if
    end if
    Send $\eta_i = (1 - \frac{1}{R_i})S_i$ and $R_i$ to mediator, and update $\beta_i$ and $\phi$.
end while
```

In order to realize this target, the results of spectrum competition should satisfy the requirement that $\frac{S_i}{S_j} = \frac{R_i}{R_j}$.

Lemma 1 *Given a set of n coexistence CRNs as $\mathcal{L}$, by utilizing Algorithm 1, the weighted fairness of allocated spectrum shares could be guaranteed in C spectrum bandwidth.*

Proof As a lot of preliminary works have been done in [14], and the weighted fairness of spectrum competition in $\sum_{i\in\mathcal{L}} R_i > \mathcal{A}$ scenario has been proved. Then we would like to prove the spectrum sharing algorithm could gain weighted fairness in $\sum_{i\in\mathcal{L}} R_i \leqslant \mathcal{A}$ scenario at this part.

In this case, suppose there exists a set of spectrum allocations $\boldsymbol{S^*}$ which is the equivalent result of spectrum competition, so for the ith CRN's spectrum share S_i^*, there could be

$$\frac{dS_i^*}{dt} = rS_i^*\left(1 - \frac{S_i^* + \sum_{j\neq i}\left(1 - \frac{1}{R_j}\right)S_j^*}{\frac{\sum_{i\in\mathcal{L}} R_i - (n-1)}{\sum_{i\in\mathcal{L}} R_i}C}\right) = 0. \qquad (9)$$

While because C is equal to $\sum_{i\in\mathcal{L}} R_i$, Eq. 9 could be simplified as:

$$S_i^* + \sum_{j\neq i}\left(1 - \frac{1}{R_j}\right)S_j^* = \sum_{i\in\mathcal{L}} R_i - (n-1). \qquad (10)$$

On the other side, since all S_i^* in $\boldsymbol{S^*}$ could realize Eq. 9, a matrix equation group could be constructed through combining all S_i^*'s Eq. 10, and the equilibrium results could be calculated.

$$S_i^* = \frac{\sum_{i\in\mathcal{L}} R_i - (n-1)}{1 + \sum_{j\neq i}\frac{R_j}{R_i}\left(1 - \frac{1}{R_j}\right)} = R_i. \qquad (11)$$

Therefore, the weighted fairness between results of spectrum competition could be guaranteed as $\frac{S_i^*}{S_j^*} = \frac{R_i}{R_j}$.

For another angle, as the weighted fairness has been maintained, if the spectrum sharing algorithm could converge to equilibrium at T_1 and keep for a long time. Then, in τ time period, objective formulation Eq. 3 could be changed to:

$$F(\boldsymbol{S}(\mathcal{L})) = 1 - \frac{\sum_{i=1}^{n} |\int_0^{T_1} \lambda_i S_i(t)dt - \lambda_i R_i T_1|}{\sum_{i=1}^{n} \lambda_i \frac{R_i}{\sum R}\mathcal{A}\tau}. \qquad (12)$$

Hence, the wasted amount of communication resources has changed to be related with convergence time T_1 but not τ. And if we could obtain a minimum time for converging, the maximized $F(\boldsymbol{S}(\mathcal{L}))$ could be get, Problem 1 could also be solved. □

4.4.2 Stability of convergence

In order to realize the maximized $F(\boldsymbol{S}(\mathcal{L}))$ we stated above, two questions should be settled, the first is maintain stable after spectrum sharing algorithm converging to equilibrium.

However, in [14], we have proved that the spectrum competition model could stably converge to equilibrium. Although there is some differences which exist in the model of this paper, no interference exists in the process of proof. So we would not prove this question in this paper, and heterogeneous CRNs' spectrum shares could maintain constantly after convergence of spectrum competition.

4.4.3 Time complexity

For the second question, a minimum time used for convergence should be obtained. Then, the analysis of this spectrum sharing algorithm's time complexity would be stated in this part.

Theorem 1 *Considering n heterogeneous CRNs coexist in a limited space with fixed available spectrum bandwidth for data transmission, the convergence time to spectrum competition equilibrium should be in log time complexity.*

Proof Suppose the ith CRN's spectrum allocation could be represented as S_{i0} at the beginning time of spectrum competition, so a sanitized data β could be held for indicating $\sum_{j\neq i}(1 - \frac{1}{R_j})S_{j0}$.

Therefore, the Eq. 8 could be depicted as:

$$\frac{dS_i}{dt} = rS_i\left(1 - \frac{S_i + \beta}{\phi}\right).$$

Through integration, there would exist

$$t = \int_{S_{i0}}^{S_{it}} \frac{1}{r S_i \left(1 - \frac{S_i + \beta}{\phi}\right)} ds_i . \tag{13}$$

By simplifying Eq. 13,

$$t = -\frac{1}{r\left(1 - \frac{\beta}{\phi}\right)} \ln \left| \frac{-\frac{r}{\phi} S_i + r\left(1 - \frac{\beta}{\phi}\right)}{S_i} \right|_{S_{i0}}^{S_{it}} \tag{14}$$

If T_c could index the convergence time, the convergence equilibrium spectrum allocation could be calculated as $S_{iT_c} = S_i^* = \frac{R_i}{\sum_{i \in \mathcal{L}} R_i} C$. Then, the time T_c could be:

$$T_c = \frac{\phi}{r(\phi - \beta)} \ln \left| \frac{S_{iTc}(\phi - \beta - S_{i0})}{S_{i0}(\phi - \beta - s_{iTc})} \right| .$$

Consequently, time complexity of the ecology-based spectrum competition model could be calculated as $T_c = O(\ln(\frac{R_i \rho C}{\sum_{i \in \mathcal{L}} R_i \rho - Ri}))$ which is log complexity. □

5 Performance evaluation

Through analyses above, *O-SCHEME* could harmonize heterogeneous CRNs well with consideration of weighted fairness and actual data transmission demands. Then, a performance evaluation would be held for demonstrating the efficiency of *O-SCHEME* in this section.

5.1 Stable equilibrium

At first, a simulation on the stable convergence of *O-SCHEME* would be proposed for verifying that this algorithm could converge to weighted fair equilibrium stably.

5.1.1 Limited spectrum bandwidth

As stated above, the outputs of *O-SCHEME* have tight relationship with total available spectrum bandwidth. So, in this simulation, 8 spectrum channels would be utilized as the total spectrum bandwidth $\mathcal{A}$, and 3 CRNs would be colocated. The 1st CRN requires 10 channels for transmission and 2nd CRN needs 6 channels through 600 iterations. While the 3rd CRN has a short communication mission, which requires 4 channels in 200–400 iterations period. Besides, in L–V competition model, the intrinsic rate of increase $r < 2$ which is proved from [28]. Hence, in this simulation, intrinsic rate we choose $r = 1.95$.

In Fig. 3, the results of first simulation have been shown out. Before 200 iterations, only *CRN*1 and *CRN*2 are competing for spectrum shares. Through a short competition period, equilibrium has been obtained at about 50 iterations, and weighted fairness has been perfectly maintained by these 2 CRNs when *CRN*1 is allocated with 5 channels and *CRN*2 has 3 channels. In 200–400 iterations period, a new *CRN*3 breaks equilibrium of competition game, but new balance between these CRNs is established quickly. While after 400 iterations, *CRN*3 completes it's mission and the other 2 CRNs move back to the primary equilibrium again.

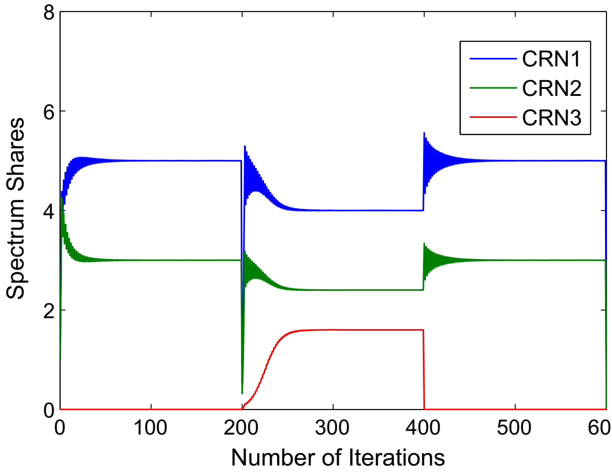

Fig. 3 Spectrum competition under limited bandwidth

In short, *O-SCHEME* could maintain weighted fairness in the limited spectrum bandwidth scenario.

5.1.2 Inadequate spectrum shares

On the other hand, when total spectrum bandwidth $\mathcal{A}$ is more than all CRNs' spectrum requirements, actual spectrum shares needs would be inadequate for the available bandwidth. In this simulation, $\mathcal{A}$ would be 25 channels, and other sets are employed the same as first simulation.

As shown in Fig. 4, before 200 iterations, *CRN*1 and *CRN*2 have gained weighted fairness and obtained their own spectrum bandwidth requirements ($S_1 = 10$ and $S_2 = 6$). While at 200 iteration, *CRN*3 joins the game and require 4 channels. But because the total spectrum requirements have not exceeded $\mathcal{A}$, a 4 channels new CRN accesses into spectrum bands for transmission without interferences on other CRNs.

Therefore, spectrum shares of heterogeneous CRNs would not be interfered by utilizing *O-SCHEME* after acquiring convergence equilibrium if overall spectrum requirements are not over $\mathcal{A}$.

5.2 Communication efficiency

Through simulations above, weighted fairness has been maintained stably by *O-SCHEME*, but more comparisons with other mechanisms are necessary.

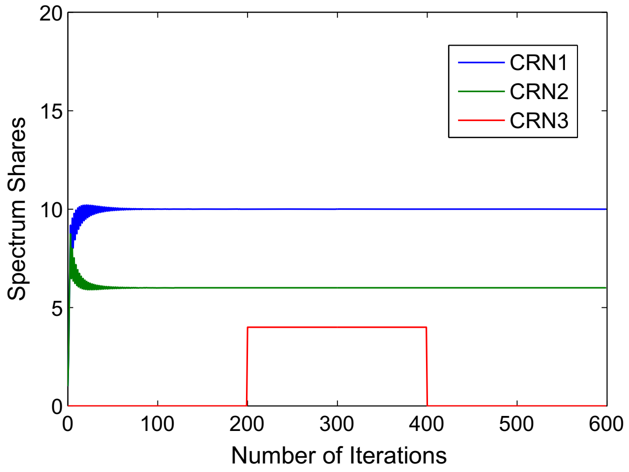

Fig. 4 Spectrum competition with inadequate QoS requirements

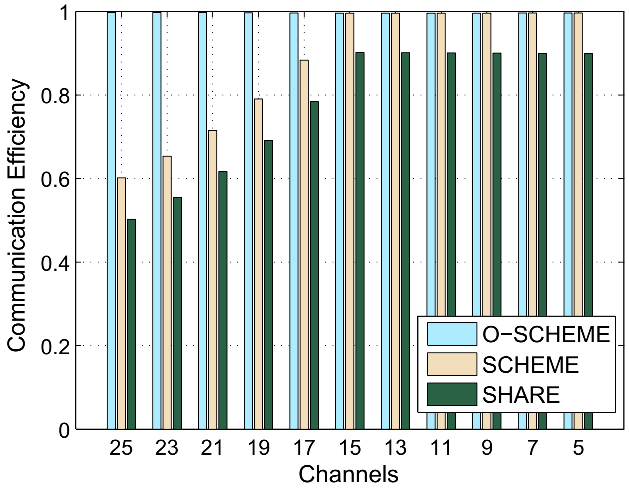

Fig. 5 Communication efficiency comparisons between different mechanisms

As the similar spectrum competition mechanisms, *SHARE-Spectrum*, *SCHEME* and *O-SCHEME* have a lot of similarities. So, we would compare these 3 mechanisms in this *communication efficiency* simulation.

In Fig. 5, a *communication efficiency* comparison between these 3 mechanisms is proposed. 5 CRNs are equipped for spectrum sharing, and their demands are transmitting 100, 200, 300, 400 and 500 packets in 100 s. All CRNs are allocated with 1 channel at the beginning. While total spectrum bandwidth $\mathcal{A}$ which they are competing decreases from 25 channels to 5 channels. Since these mechanisms have same centralized information exchange system, the ratio between their algorithm iteration and real time slot is set as 1. And suppose channels' speed coefficient λ is the same as 1, the spectrum channels requirements could be calculated as 1, 2, 3, 4, 5 respectively. Then, normalized *communication efficiency* $F(\boldsymbol{S}(\mathcal{L}))$ could be depicted by the bar figure.

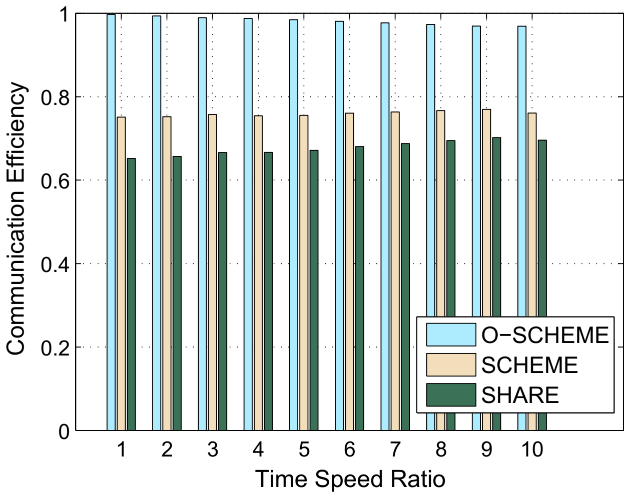

Fig. 6 Communication efficiency comparisons between different time ratio

Before $\mathcal{A}$ decreasing to 15, overall spectrum requirements are not enough for competition. In this case, *O-SCHEME* could maintain nearly maximized results by reducing communication resources waste according to CRNs' demands in the process of competition, while other 2 mechanisms have much lower spectrum utilization. As the decreasing of $\mathcal{A}$, outcomes of *SCHEME* and *SHARE-Spectrum* are increasing because wasteful spectrum resources are decreasing too. When $\mathcal{A}$ decreases under 15, total available spectrum channels could not afford heterogeneous CRNs' spectrum requirements. However, *O-SCHEME* could also obtain the best *communication efficiency* since which could fully utilize spectrum resources. And *SCHEME* could get the best outcome too since weighted fairness allocations of spectrum have been gained. While *SHARE-Spectrum* could not reach the top on account of it's own algorithm's defects.

Consequently, the results figure out that *O-SCHEME* has a better performance on the on-demand spectrum sharing. Whereas, as the convergence time has important impact on *O-SCHEME* data transmission result, we would like to simulate the *communication efficiency* comparisons in different ratios between algorithm iteration and real time slots. So, 20 available channels would be utilized in this simulation. And the time ratio would be set from 1 to 10 which means 1 iteration would cost from 1 to 10 time slots, since low ratio would cause high convergence speed and more data would be sent after spectrum shares equilibrium which is not helpful on the analysis of time impacts. While the demands of data transmission would be employed as the last simulation.

As stated in Fig. 6, *communication efficiency* comparisons between different time ratios are described. The result of *O-SCHEME* is decreasing when time ratio increases, because *O-SCHEME* is designed for on-demand spectrum sharing and the lower iterations in the process of data transmission,

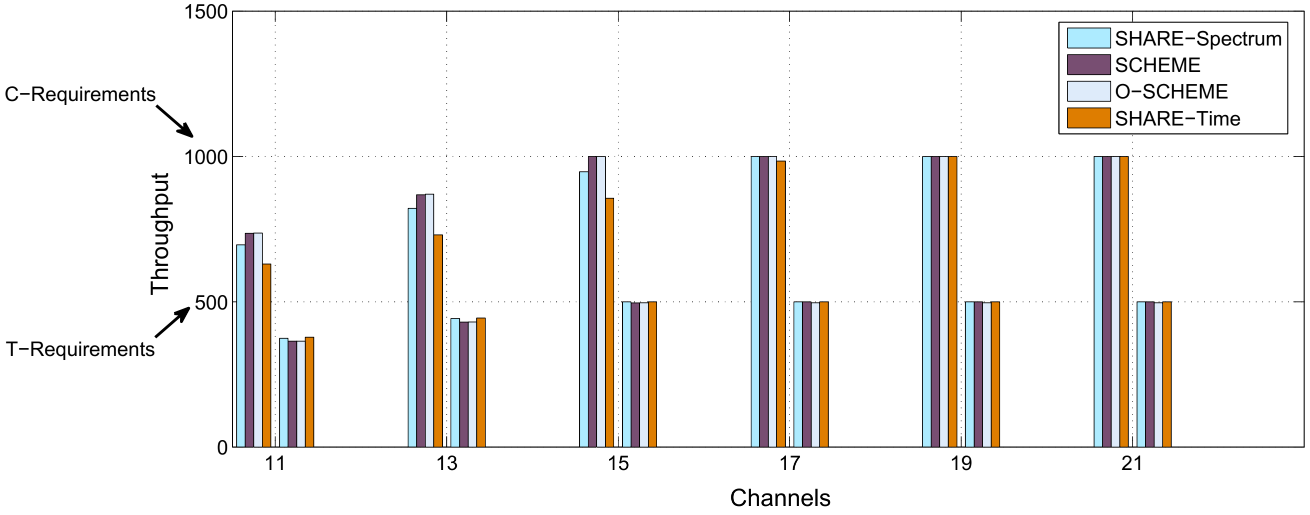

Fig. 7 Throughput comparison between different coexistence mechanisms

the more impacts on throughput. While other 2 mechanisms could maintain the same level in different data speeds since larger communication resources wastes are acquired by them at the beginning of convergence and speed changes have less impacts on their results. Even so, *O-SCHEME* could give out much better performance on on-demand spectrum sharing.

5.3 Throughput

After above simulations, *O-SCHEME* could gain the best performance on the on-demand spectrum sharing with other coexistence mechanisms. But the comparison mechanisms are homologous with *O-SCHEME*, there is lack of strong evidence to prove that *O-SCHEME* could do better. Hence, we would like to compare *O-SCHEME* with *SHARE-Time* by throughput in this simulation.

As shown in [20], *SHARE-Time* focuses on the coexistence between CSMA CRNs and TDMA CRNs, so this simulation would be held under these 2 types networks. While by employing simulation sets in [20], 1 CSMA packet would cost 2 time slots and it's arrival pattern would be set as Poisson distribution in which the arrival rate is defined as 0.5. And 1 TDMA packet would cost 10 time slots, the ratio of time shares between CSMA frames and TDMA frames is 1:2.

Combining all sets stated above, we could get that the proportion of transmitted packets amounts in unit time between CSMA CRN and TDMA CRN is 2:1. Thus, the target of this simulation could be set as that CSMA CRN should send 1000 packets and TDMA CRN should send 500 packets in 500 time slots, which suggests that CSMA needs 5 channels and TDMA needs 10 channels for data transmission to finish the task.

Through the last simulation, few differences would be generated by utilizing different time ratios. Then, the time ratio of the 3 spectrum type coexistence mechanisms would be set as 1. The detailed data transmission settings of these 3 mechanisms would also employ the settings of *SHARE-Time*. By increasing total spectrum bandwidth from 11 channels to 21 channels, the results of throughput comparison would be depicted in Fig. 7.

In Fig. 7, bar figures represent overall throughput by utilizing different coexistence mechanisms. Throughput comparisons are stated in CSMA and TDMA types separately, CSMA throughput comparisons are placed at the left side of channels' marks, while TDMA throughput comparisons are placed at right side. *C-Requirement* indicates CSMA CRN's data transmission requirement which needs to send 1000 packets in 500 time slots, and *T-Requirement* indicates TDMA CRN's.

Consequently, as shown in the figure, from 11 channels to 15 channels, total available spectrum bandwidth is not enough for the mission needs. Although TDMA packets sending amounts of these mechanisms are nearly the same, the performance of *O-SCHEME* on CSMA packets transmission has about 20% advantage than *SHARE-Time*. While because *O-SCHEME* and *SCHEME* are homologous, outputs of them are the same without doubts. But *SHARE-Spectrum* does worse on the CSMA packets transmission since errors exist in allocated spectrum bandwidth calculation. However, when $\mathcal{A}$ increases from 15 to 21, the allocated channels amount of *O-SCHEME* would not increase with $\mathcal{A}$, so the results of *O-SCHEME* are just the target which services required. The packets wastes generated by *SCHEME* and *SHARE-Spectrum* also exist and increase with $\mathcal{A}$. On the other side, even $\mathcal{A}$ increases to 17 channels where the 2 spectrum type mechanisms gain at least 5% higher on throughput, the throughput of CSMA packets transmitted by *SHARE-Time* has not reached the target as *O-SCHEME* does, the specific application efficiency on weighted fairness spectrum allocation of *SHARE-Time* has a big gap from *O-SCHEME*.

As a result, *O-SCHEME* could complete the data sending mission in different scenarios with maximum *communication efficiency*, and have a better performance than other heterogeneous CRNs coexistence mechanisms.

6 Conclusion

In this paper, a novel *On-demand ecology Species Competition based HEterogeneous networks coexistence MEchanism* has been provided to harmonize heterogeneous CRNs in TVWSs and satisfy CRNs' real communication demands. By employing IEEE 802.19.1 system, an indirect negotiation system is constructed for heterogeneous CRNs. And through the *On-demand ecology Species Competition Algorithm*, we have successfully settled the on-demand spectrum sharing allocation tasks: (1) heterogeneous CRNs spectrum bandwidths dynamical adjustments according to spectrum requirements, (2) weighted fairness spectrum shares allocation, and (3) high efficient spectrum utilization without communication resources waste. Analytical and simulation results figure out that *O-SCHEME* could converge to a stable and fair optimum on-demand equilibrium fast.

However, this mechanism is only suitable for CRNs coexistence without consideration of *Primary Users*, we would like to study this field in future.

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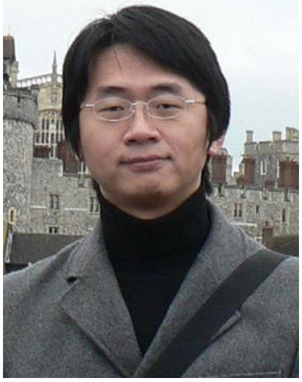

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