Ecology-based Coexistence Mechanism in Heterogeneous Cognitive Radio Networks

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***Abstract*—Recently, tremendous utilization of wireless networks has led to sever scarcity of radio spectrum resources. TV White Spaces (TVWSs) as novel bands enabling Cognitive Radio (CR) technology to improve spectrum resources utilization, have attracted significant standardisation efforts such as IEEE $802.11af$, IEEE $802.16h$ and 802.22. As these heterogeneous networks may operate on the same channels of TVWSs, network coexistence problem cannot be avoided and is particularly challenging given the heterogeneous MAC/PHY layer protocols and operation parameters (e.g., tx power) employed in coexisting networks. In this paper, we develop a coexistence mechanism called *ecological Species Competition based HEterogeneous networks coexistence MEchanism* (*SCHEME*). Inspired by ecology based species competition model, *SCHEME* uses an ecological spectrum allocation method to assign available spectrums. Through both theoretical and simulation analysis, we demonstrate that *SCHEME* can achieve stable and fair spectrum allocation among coexisting networks.**

Keywords*—Cognitive Radio Networks, Ecology based Algorithm, Networks Coexistence.

I. Introduction

The last two decades have witnessed ubiquitous utilization of wireless networks devices around the world. Due to redundant spectrum occupations, only limited spectrum resources can be used for novel network deployment. Since intelligent perception and self-adaption nature, Cognitive Radio (CR) technology are presented to solve challenges for maximizing limited spectrum resources utilization and mitigating interference between primary networks and secondary networks as well as among secondary networks. Meanwhile, as TV wireless signals are massively transferred to digital wired standard, vacant TV bands (ie. VHF/UHF $54-698MHz$) are available as "TV White Spaces" (TVWSs) for new CR networks operation [1]. Consequently, a number of CR networking standards have been provided for this new spectrum band, e.g. IEEE 802.22 Wireless Regional Area Networks (WRAN) [2], IEEE $802.11af$ (WiFi over TVWS) [3], IEEE $802.16h$ [4] and ECMA 392 (WPAN over TVWS) [5] etc.

These networks may operate on overlapping spectrum channels and are heterogeneous in many aspects such as MAC/PHY layer protocols, transmission power levels [6]. Hence, heterogeneous CR network coexistence becomes a pressing problem in enabling efficient utilisation of TVWSs. Most CR network standards have proposed coexistence mechanisms, but all these mechanisms focus on the coexistence of homogeneous networks. IEEE 802.22 has proposed two types of coexistence mechanisms (networks coexistence and cells coexistence). At networks level, coexistence mechanism harmonizes neighbor networks' Base Stations' communication, while at cells level, a meticulous mechanism is introduced to conquer the problem between different terminals in same network [2]. IEEE $802.16h$ provides a specified coexistence control channel for control information transmission and two degree mechanisms (uncoordinate mechanism and coordinate mechanism) to realize different networks coexistence [4]. A *Beacon Period* (BP) mechanism is deployed in ECMA 392 networks self-coexistence to eliminate intra network frame collision, and a three-type of coexistence scenarios solution scheme is added to solve homogeneous networks conflicts [5]. IEEE 802.19.1 is a novel standard specialized proposed for heterogeneous networks coexistence in TVWSs. IEEE 802.19.1 composes of *Coexistence Manager* (CM), *Coexistence Enabler* (CE), *TVWS Database* and *Coexistence Discovery and Information Sever* (CDIS) which are all designed to communicate with heterogeneous networks they equipped on as coordinator. By harmonizing different networks' characteristics, heterogeneous networks coexistence can be realised [7].

Only a handful heterogeneous coexistence mechanisms in TVWSs have been developed. Zhao *et al.* proposed a *Fairness-oriented Media Access Control* (FMAC) protocol, including cooperative spectrum sensing mechanism for primary users' location detecting and novel detection three-state model for signal diagnosing, to coexist between heterogeneous secondary user networks and between primary user networks and secondary user networks in [8], [9]. In [10], Bian *et al.* presented *Beacon Transmission* and *Quiet Period* mechanisms to coexist heterogeneous networks by coordinating different networks' frames via IEEE 802.19.1 mediator. Similarly, a biology based framework was developed with IEEE 802.19.1 by Bian *et al.* [11], [12]. An ecology population competition based spectrum allocation architecture were proposed in [11].

Motivated by above observation, an *ecological Species Competition based HEterogeneous networks coexistence MEchanism* (*SCHEME*) is developed in this paper to enable collaborative heterogeneous coexistence among CR networks and ensure their spectrum allocation fairness. As *SCHEME* is

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inspired by *Symbiotic Heterogeneous coexistence ARchitecturE* (*SHARE*) in [11], [12], an indirect mediator mechanism is also employed in *SCHEME*. And as *SCHEME* name indicates, *SCHEME* is a mechanism based on ecological species population competition, which employed an *ecology inspired spectrum allocation sharing* algorithm to enable each network autonomously determines its own spectrum bandwidth without direct negotiation between competing networks. Our analysis and simulation indicate *SCHEME* improves spectrum resources utilization and guarantees coexisting networks fairness.

The rest of this paper is organized as follow, a general technology background introduction of mediator system and ecology based mechanism is proposed in section II. In section III, an overview of *SCHEME* is presented. The detailed algorithm and proof of *SCHEME* are proposed in section IV. In section V, performance of *SCHEME* is evaluated by simulations. And the conclusion is presented in section VI.

II. Technical Background

Our solution *SCHEME* employs IEEE 802.19.1 mediator for indirect coordination among coexisting networks and uses an ecology-based mechanism to allocate spectrum resources. In this section, we review technical background on the mediator system and the ecology-inspired model used in *SCHEME*.

A. Mediator System

IEEE 802.19.1 is a generic coexistence protocol specifically proposed for coordinating heterogeneous CR networks' coexistence [7]. Each CR network terminal needs to equip IEEE 802.19.1 devices for joining in mediator system, the local architecture of IEEE 802.19.1 is illustrated in Fig. 1.

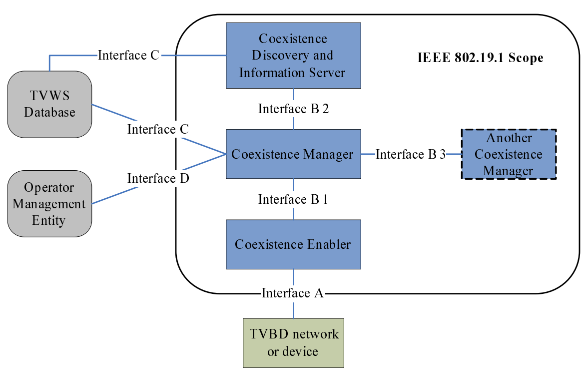


Fig. 1: IEEE 802.19.1 System Architecture

There are three main components Coexistence Manager (CM), Coexistence Enabler (CE) and Coexistence Discovery and Information Server (CDIS) in IEEE 802.19.1.

- CM is the core component. As local decision maker, CM is responsible for exchanging coexistence information and other control messages with CE, and communicating with other CMs or TVWSs Database which is designed for storing Primary Users (PU) occupation channel lists.
- CE guarantees stable connection between CM and TV Band Devices (TVBD) or TV Band CR Networks.
- The function of CDIS is to support information about other CMs or PUs from TVWS Database.

B. Ecology inspired model in SHARE

In [11], [12], Bian *et al.* proposed an ecology based spectrum competition model to describe relationship between heterogeneous networks' spectrums allocation sharing in TVWSs. As original model, *Lotka-Volterra* (L-V) *predator-prey* equation is a basic *predator-prey* model to research population competition relationship between different species groups [13]. In *L-V* model, multiple different species groups' competition for limited nourishments is analogous to heterogeneous networks competition for limited spectrum, which is shown below:

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

As illustrated in (1), N_i is ith predator specie's population size, $\frac{dN_i}{dt}$ represents population dynamics of specie i. And K_i is maximum population size of specie i, r_i is intrinsic rate of increase, $\alpha_{i,j}$ is mutual influence between specie i and j.

In *SHARE* [11], [12], Bian analogizes the specie population N_i to spectrum bandwidth unit S_i of CR network i, therefore, a spectrum competition model is structured as (2):

$$\frac{dS_i}{dt} = r S_i \left(1 - \frac{S_i + \alpha \sum_{j \neq i} S_j}{C}\right). \tag{2}$$

Because there is no individual difference between heterogeneous networks spectrum, intrinsic rate r, competition coefficient α and the maximum spectrum bandwidth C became same constant in heterogeneous networks.

However, we have found an error in the demonstration in [11], [12]. Suppose network i requires R_i units bandwidth at this time, the real equivalent point of *SHARE* should be $S_i = \frac{R_i C}{1+(\sum_{i \in \mathcal{L}} R_i - 1)\alpha}$ rather than original result $S_i = \frac{R_i C}{\sum_{i \in \mathcal{L}} R_i}$, where $\mathcal{L}$ denotes channel sets of heterogeneous CR networks. Obviously, the correct conclusion is related to α, only when $\alpha = 1$ these two results are the same. And this conclusion is clearly not the optimum result. Hence, due to the unperfect conclusion, *SHARE* has just achieved a sub-optimum solution of spectrum allocation fairness among coexisting networks.

III. Overview of SCHEME

To find the optimum solution, we proposed *SCHEME*. In this section, A comprehensive overview of *SCHEME* is presented, including *system model* and *main target*.

A. System model

Suppose spectrum bandwidth in TVWSs are organised in K parts, we define one part is one *unit* spectrum bandwidth which is minimum unit of spectrum in this paper. And there are n coexistence CR networks co-located, let $\mathcal{L}$ indexes n CR networks, hence, given $\boldsymbol{S}(\mathcal{L}) = \{S_1, S_2, \ldots, S_n\}$ represented these networks' spectrum allocations. Because $\boldsymbol{S}(\mathcal{L})$ and other parameters related to spectrum allocation are variable as time goes on, we would simplify these parameters without time denote full version (i.e. $S_i = S_i(t)$), and define all parameters used are at the same time slot. All these sets of CR networks would be converged to IEEE 802.19.1 mediator by CR networks' TVBDs. The particular settings are listed as follow:

- **Number of Spectrum Units**. As the spectrum access competition is not main focus of this paper, there would not exist CR network which is allocated no spectrum for transmission, and each CR network should have at least one communication spectrum unit, so, overall spectrum units K must be more than CR networks number n.

- **Bandwidth**. We define $\boldsymbol{S}(\mathcal{L})$ as all CR networks' spectrum allocation scheme. And for heterogeneous CR networks' QoS requirements, R_i is employed to denote network i's bandwidth requirement which should be satisfied.
- **Mediator**. In this paper, an indirect IEEE 802.19.1 mediator system is equipped because of distributed heterogeneous characteristic of CR networks. As IEEE 802.19.1 devices are matched with CR networks' terminals, parameters of spectrum allocation can be easily sent to TVWS database. Correspondingly, some sanitized data is calculated from the uploaded parameters to guarantee easy utilization and indirect coordination between heterogeneous networks. So that, the indirect interaction between heterogeneous CR networks is established.

B. Main Target

In *SCHEME*, the main purpose is to allocate appropriate spectrum units to correspond network, and guarantee the fairness between allocated networks spectrum bandwidths.

*1) **Spectrum Allocation Sharing**:* For spectrum sharing, suppose K spectrum units bandwidth exist for n CR networks communication. Because each network should guarantee at least one unit transmission spectrum, $K > n$ is essential condition for this paper, which means there exist $K - n$ additional units spectrum should be allocated, how to design allocation scheme is key problem.

As we presented above, $\boldsymbol{S}(\mathcal{L})$ represents overall spectrum allocation sets of CR networks, and at least one unit spectrum is guaranteed for network's basic communication demand, $S_i \in [1, K - n + 1]$ can be figured out easily.

*2) **Allocation Fairness**:* Only spectrum allocation sharing is not the final destination, a fairness spectrum assignment mechanism for each CR network is needed.

Hence, in TVWSs, given n CR networks coexist in a limited space, suppose $\mathcal{L}$ indexes these networks. Then, $\boldsymbol{S}(\mathcal{L})$ denotes spectrum bandwidth sets and $\boldsymbol{R}(\mathcal{L})$ describes bandwidth requirements. As our objective is to guarantee fairness between heterogeneous CR networks, which means networks need to share spectrum with each other to get an equivalent point where each network's bandwidth is nearest to requirement spectrum (a.k.a $\frac{S_i}{S_j} = \frac{R_i}{R_j}$). So that a simple formulation is proposed to depict overall fitness status of coexistence networks.

$$F(\boldsymbol{S}(\mathcal{L})) = 1 - \sum_{i \in \mathcal{L}} \left| \frac{S_i}{K} - \frac{R_i}{\sum_{i \in \mathcal{L}} R_i} \right|. \tag{3}$$

In (3), as there is no specific constraints for spectrum, we use K to define maximum spectrum capacity. Hence, the gap between real-time spectrum bandwidth and requirement can be easily displayed as ratio difference between them $\frac{S_i}{R_{max}} - \frac{R_i}{\sum_{i \in \mathcal{L}} R_i}$. And sum up absolute values of these differences, the overall networks' fitness can be expressed. For easy understanding, we added 1 to minus these summation performed like $F(\boldsymbol{S}(\mathcal{L}))$, so, the $F(\boldsymbol{S}(\mathcal{L}))$ gets closer to 1 means overall fairness of spectrum sharing is becoming better.

Consequently, the *fairness spectrum allocation* problem can be formulated to determine heterogeneous CR networks' spectrum bandwidth sharing amounts.

Problem 1: Given n coexisting heterogeneous CR networks, with K vacant TVWSs spectrum units. The following problem should be solved for finding spectrum sharing vector $\boldsymbol{S}(\mathcal{L})$,

$$Maxmize \quad F(\boldsymbol{S}(\mathcal{L})) = 1 - \sum_{i \in \mathcal{L}} \left| \frac{S_i}{K} - \frac{R_i}{\sum_{i \in \mathcal{L}} R_i} \right|$$

$$Subject\ to \quad \frac{S_i}{S_j} = \frac{R_i}{R_j}, R_i \geqslant 1, K - n + 1 \geqslant S_i \geqslant 1, \forall i \in \mathcal{L}$$

IV. Ecological Species Competition based Heterogeneous Coexistence Mechanism

In this section, we present *SCHEME* in detail, and prove its performance guarantee in fairness and stability.

A. Ecology based Spectrum Competition Model

*1) **spectrum competition model**:* In section.II, we have illustrated *SHARE* competition model in (2). But a misleading result gives *SHARE* an unperfect sub-optimum consequence. Hence, a precise spectrum competition model should be proposed:

$$\frac{dS_i}{dt} = rS_i \left(1 - \rho \frac{S_i + \sum_{j \neq i} \alpha_{i,j} S_j}{K} \right) \tag{4}$$

as shown in (4), for dynamic bandwidth requirements, a novel QoS constraint parameter ρ is added, while mutual interference $\alpha_{i,j}$ is also different between networks.

Next, we would like to show how to structure QoS constraint parameter ρ and coexistence coefficient $\alpha_{i,j}$.

*2) **QoS constraint**:* In *SCHEME*, ρ represents bandwidth requirements' influence to K. Therefore, relationship between K and ρ could be described as follow:

$$\frac{K}{\rho} = \frac{\sum_{i \in \mathcal{L}} R_i - n + 1}{\sum_{i \in \mathcal{L}} R_i} K. \tag{5}$$

where n is number of coexistence networks, while R_i is spectrum requirement of network i. In (5), $\frac{K}{\rho}$ is transformed spectrum constraint based on bandwidth requirements clearly. As one unit spectrum is guaranteed for each network, $\sum_{i \in \mathcal{L}} R_i - (n-1)$ is maximum required spectrum one network could occupy, and $\frac{\sum_{i \in \mathcal{L}} R_i - n + 1}{\sum_{i \in \mathcal{L}} R_i}$ means one network maximum required spectrum ratio. Hence, in real competition model, total spectrum networks compete for is formulated as $\frac{K}{\rho}$.

Consequently, logical maximum spectrum constraint networks competing based on QoS requirements is guaranteed.

*3) **Mutual Interference**:* To another extent, coexistence coefficient $\alpha_{i,j}$ is the representation of spectrum competition between network i and j. To some degree, competition between spectrum is the same, hence, there is no difference between from network i to j and from network i to $j + 1$. All in all, for network i, spectrum competition only exists between itself and other networks. Therefore,

$$\alpha_{i,1} = \alpha_{i,2} = \ldots = \alpha_{i,j} = \alpha_i$$

for α_i, it is the characteristic denoted networks' competition. In *SCHEME*, fairness is the final criterion of networks' competitiveness. So, α_i can be depicted as:

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

For network i, product of α_i and S_i denotes influence from network i to other networks. Hence, $R_i - 1$ means one basic spectrum unit must be subtracted. So that, with this proportion, competition shares of network's real-time bandwidth could be calculated simply. And competition portion of S_i is the only part which can be used in other networks' calculations.

B. Spectrum Sharing Algorithm

With corresponding QoS parameters, spectrum allocation model (4) could be transformed to another form:

$$\frac{dS_i}{dt} = rS_i\left(1 - \frac{S_i + \sum_{j\neq i}\left(1 - \frac{1}{R_j}\right)S_j}{\frac{\sum_{i\in\mathcal{L}} R_i - n + 1}{\sum_{i\in\mathcal{L}} R_i}K}\right) \tag{6}$$

which is too complicated for distributed coexistence between heterogeneous CR networks with IEEE 802.19.1 mediator. Hence, a transformation of (6) should be presented.

Suppose there is an η_i, which can denote network i's influence to other networks. This η_i should be:

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

then, a sanitized data β_i can be concluded to summarize other networks' influences to network i:

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

And because parameter ρ is related to all networks in TVWSs, while networks' spectrum requirements are dynamic and non-transcendental. For individual CR network, η and R uploading with β and ρ downloading from mediator should be accomplished for coexistence information exchanging.

Then, a novel spectrum sharing algorithm pseudo-code is proposed in *algorithm.*1, and description is presented as below:

(i) At first, as a QoS based spectrum sharing algorithm, the current required spectrum bandwidth R_i must be gained.
(ii) Before iteration, mutual influence parameter β_i and overall QoS constraint ρ should be updated from mediator.
(iii) If R_i changed, which means QoS requirements of CR network i has been different 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 should be modified to change spectrum sharing, and follow the pace of networks' competition.
(v) 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 ρ would be downloaded for next iteration.
(vi) 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.

Algorithm 1 Spectrum Sharing Alogrithm

Input: intrinsic rate r, ith network's spectrum requirement R_i, ith network's influence η_i, the sanitized data β_i, overall spectrum requirements constraints ρ.
Output: ith network's spectrum share S_i.

Collect current required spectrum bandwidth R_i.
Update β_i and ρ 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**
    $S_i = S_i + \frac{dS_i}{dt}$
  end if
  Send $\eta_i = (1 - \frac{1}{R_i})S_i$ and R_i to mediator, and update β_i and ρ.
end while

C. Stability and Equilibrium Analysis

After introduction of model and algorithm, we would like to prove these model and algorithm are workable and stable.

*1) **Fairness convergence**:* Firstly, if the competition model and spectrum allocation algorithm could achieve fairness convergence equilibrium defined in Problem.1 should be proved.

Lemma 1. *Given n coexistence CR networks co-located in $\mathcal{L}$, by using the spectrum allocation mechanism in algorithm.1, the fairness can be guaranteed in K spectrum units.*

Proof: Suppose network $i \in \mathcal{L}$ has a spectrum requirement R_i, equivalent problem would become if results of *SCHEME* is equal to the ratio of QoS requirements. So, we would obtain outcome from *SCHEME* at first, suppose S_i^* denotes result of network i when equilibrium has been reached, which can be described as follow formulation:

$$\frac{dS_i^*}{dt} = rS_i^*\left(1 - \rho\frac{S_i^* + \sum_{j\neq i}\alpha_j S_j^*}{K}\right) = 0. \tag{7}$$

By simplifying (7), we can easily derive that

$$S_i^* + \sum_{j\neq i}\alpha_j S_j^* = \frac{K}{\rho}. \tag{8}$$

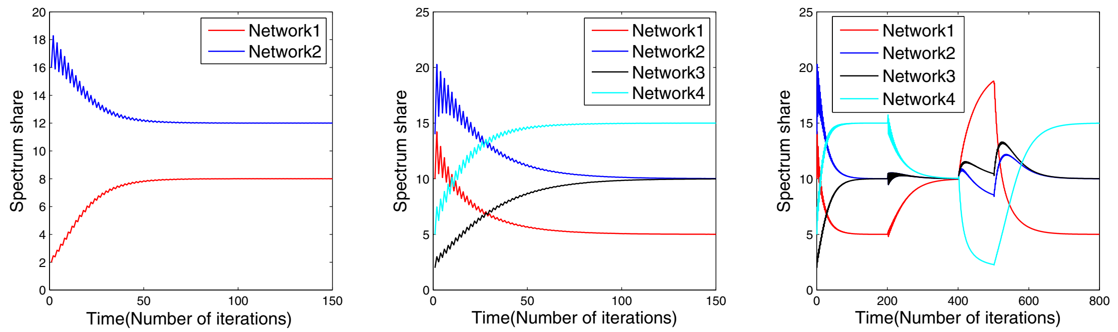
For all S_i^*, equation (8) is workable. Then, put all α and ρ into (8) and simplification, all S_i^* can be calculated out,

$$S_i^* = \frac{K}{\rho(1 + \sum_{j\neq i}\alpha_j\frac{1-\alpha_i}{1-\alpha_j})} = \frac{R_i}{\sum_{i\in\mathcal{L}} R_i}K \tag{9}$$

and thus $\frac{S_i^*}{S_j^*} = \frac{R_i}{R_j}$, which guarantees the spectrum allocation fairness and satisfies QoS requirements. ■

*2) **Stability**:* As we get convergence equilibrium above, we should prove these results are stable which means these consequences are workable and robust.

Theorem 1. *Let n denotes number of different CR coexistence networks. Equation (7) describes the n dimension system converged to equilibrium $S_i^* = \frac{R_i}{\sum_{i\in\mathcal{L}} R_i}K$ is stable.*



(a) Two Networks Coexistence (b) Four Networks Coexistence (c) Four Networks Coexistence Stability

Fig. 2: Networks Coexistence

Proof: Suppose there are n heterogeneous coexistence networks, and S_i^* represents the spectrum allocated shares when network's competition converged to equilibrium. So, by Lemma1, we can easily figure out (9). And to prove the equilibrium $\boldsymbol{S}^*$ is stable, we would like to linearize this equation at equivalent point. Hence, given $\boldsymbol{S} = [s_1, s_2, \cdots, s_n]$ denotes the spectrum shares allocation of different networks. Equation (7) can be exchanged to another formation:

$$G_i(\boldsymbol{S}) = rS_i\left(1 - \rho\frac{S_i + \sum_{j\neq i}\alpha_j S_j}{K}\right). \tag{10}$$

Let $\Delta S_i = S_i - S_i^*$. Equation (10) would be linearized as

$$\begin{aligned} G_i(\boldsymbol{S}) &= G_i(\boldsymbol{S^*}) + \sum_{i\in\mathcal{L}}\left(\frac{\partial G_i(\boldsymbol{S})}{\partial S_i}\,|_{S_1^*,S_2^*,\ldots,S_n^*} \cdot\Delta S_i\right) \\ &= \frac{r\rho R_i}{\sum_{i\in\mathcal{L}} R_i}\left(-\Delta S_i - \sum_{j\neq i}\alpha_j\Delta S_j\right). \end{aligned}$$

So, suppose $l = \sum_{i\in\mathcal{L}} R_i$, a $n * n$ Jacobian matrix can be derived out from above:

$$\boldsymbol{A} = -\begin{vmatrix} \frac{r\rho R_1}{l} & \frac{r\rho R_1}{l}\alpha_2 & \frac{r\rho R_1}{l}\alpha_3 & \cdots & \frac{r\rho R_1}{l}\alpha_n \\ \frac{r\rho R_2}{l}\alpha_1 & \frac{r\rho R_2}{l} & \frac{r\rho R_2}{l}\alpha_3 & \cdots & \frac{r\rho R_2}{l}\alpha_n \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{r\rho R_n}{l}\alpha_1 & \frac{r\rho R_n}{l}\alpha_2 & \frac{r\rho R_n}{l}\alpha_3 & \cdots & \frac{r\rho R_n}{l} \end{vmatrix}$$

where all elements in $\boldsymbol{A}$ are coefficients of $\boldsymbol{S}$. Hence, if $\boldsymbol{A}$ can calculate out to stable convergence equilibrium, the equivalent result of spectrum allocation sharing algorithm also can be proved to be stable. So, for matrix $\boldsymbol{A}$, the eigenvalues could be calculated from follow formulation,

$$\begin{aligned} &\prod_{i\in\mathcal{L}}\left(-\frac{r\rho R_i}{l} - \lambda\right) + (n-1)\prod_{i\in\mathcal{L}}\left(-\frac{r\rho R_i}{l}\right)\prod_{i\in\mathcal{L}}(\alpha_i) \\ &-\sum_{i\in\mathcal{L}}\left(\left(-\frac{r\rho R_i}{l} - \lambda\right)\prod_{j\neq i, j\in\mathcal{L}}\left(-\frac{r\rho R_j}{l}\right)(\alpha_j)\right) = 0, \end{aligned}$$

where λ is eigenvalue of matrix $\boldsymbol{A}$, then, this equation could be simplified to be as follow,

$$\begin{aligned} &(-1)^n\left(a_0 + (n-1)\prod_{i\in\mathcal{L}}\left(\frac{r\rho R_i}{l}\alpha_i\right) - \sum_{i\in\mathcal{L}}\frac{\prod_{i\in\mathcal{L}}\frac{r\rho R_i}{l}\alpha_i}{\alpha_i}\right. \\ &\left. + \sum_{i\in[2,n]} a_i\lambda^i + \left(a_1 - \sum_{i\in\mathcal{L}}\frac{\prod_{i\in\mathcal{L}}\left(\frac{r\rho R_i}{l}\alpha_i\right)}{\alpha_i}\right)\lambda\right) = 0 \end{aligned}$$

in which, a_i is parameter expanded by $\prod_{i\in\mathcal{L}}\left(\frac{r\rho R_i}{l} + \lambda\right)$, as r, ρ, l and R_i are all positive, a_i could not be negative coefficient. Therefore, coefficients of λ^2 to λ^n would not be negative, meanwhile, a_0 can easily calculated as $\prod_{i\in\mathcal{L}}\frac{r\rho R_i}{l}$ while QoS constant $0 < \alpha < 1$, hence, it could figure out that

$$\begin{aligned} &a_0 + (n-1)\prod_{i\in\mathcal{L}}\left(\frac{r\rho R_i}{l}\alpha_i\right) - \sum_{i\in\mathcal{L}}\frac{\prod_{i\in\mathcal{L}}\frac{r\rho R_i}{l}\alpha_i}{\alpha_i} \\ &= \prod_{i\in\mathcal{L}}\frac{r\rho R_i}{l}\left(1 + (n-1)\prod_{i\in\mathcal{L}}\alpha_i - \prod_{i\in\mathcal{L}}\alpha_i\sum_{i\in\mathcal{L}}\frac{1}{\alpha_i}\right) > 0. \end{aligned}$$

Similarly, parameter a_1 also could be derived out as $\sum_{i\in\mathcal{L}}\frac{\prod_{i\in\mathcal{L}}(\frac{r\rho R_i}{l})}{\frac{r\rho R_i}{l}}$. Because of $0 < \alpha < 1$, it is obvious that $a_1 - \sum_{i\in\mathcal{L}}\frac{\prod_{i\in\mathcal{L}}(\frac{r\rho R_i}{l}\alpha_i)}{\alpha_i}$ is positive. As a result, all coefficients of λ are positive, if the equation is equal to 0, λ must be negative, the eigenvalues of $\boldsymbol{A}$ are negative. According to stability theory, the spectrum share allocation system is stable. The heterogeneous coexistence networks would converge to stable equivalent point $\boldsymbol{S^*} = [s_i^* | s_i^* = \frac{R_i}{\sum_{i\in\mathcal{L}} R_i}K, \forall i\in\mathcal{L}]$. ■

V. Performance

In this section, we would like to present simulated performance of *SCHEME* in two parts. First step shows stability of convergence equilibrium and dynamic adaptation capacity of spectrum sharing scheme. And second step, fairness comparison between *SCHEME* and *SHARE* would be proposed.

A. Stable Equilibrium

*1) **Convergence Equilibrium**:* The first step is to simulate networks converge to equilibrium, we simulate two coexistence CR networks co-located in limited space with 20 spectrum units could be utilized for transmission. Then, the required spectrum values are fixed as $R_1 = 10$ and $R_2 = 15$, which indicates that *network-1* needs 10 units spectrum and *network-2* needs 15 units spectrum to transmit information. And in L-V competition model, the intrinsic rate of increase $r < 2$ which is proved from [13]. Hence, in this simulation, intrinsic rate we choose $r = 1.95$. Therefore, first simulation is two networks, which have two initial spectrum shares $S_1 = 2$ and $S_2 = 16$ respectively, converge to their own equivalent points. The convergence performance is shown in Fig.2(a), *network-1*'s allocated spectrum bandwidth increases from 2 units to 8 units, correspondingly, *network-2* decreases from 16 units to 12 units, which meets QoS requirements and fairness.

And for an additional certification, four networks coexistence scenario is added. These four networks have 40 units spectrum bandwidth for transmission, they also have initial spectrum bandwidth $S_1 = 10$, $S_2 = 14$, $S_3 = 2$ and $S_4 = 5$ respectively. And their required bandwidth is $R_1 = 6$, $R_2 = 12$, $R_2 = 12$ and $R_4 = 18$. Undoubtedly, the required equilibrium is converged which is shown in Fig.2(b).

*2) **Stability**:* The second step is to simulate networks coexistence scheme convergence equilibrium is stable. Fig.2(c) shows out the stability, in which there are four networks. Initially, the sets of four networks are the same as Fig.2(b). Hence, before 200 iterations, performance is similar to Fig.2(b). Then, from 200 to 400 iterations, four networks' bandwidth requirements are all changed to 20 units spectrum, so it is easy to find out these four networks' spectrum bandwidth is converged to 10 units according to ratio of their required spectrum. And from 400 to 500, the required spectrum shares are changed to 50, 20, 25, 5 units. Without waiting for equivalent point convergence, spectrum requirements changed to 10, 20, 20, and 30 after 500 iterations. Hence, the result changed frequently from 400 to 800 iterations. Although final QoS requirements are different from Fig.2(b), the ratio are the same, so convergence equilibrium is the same. Concisely, the spectrum allocation sharing scheme is stable convergence.

B. Fairness

In this part, we would like to present fairness comparison between *SCHEME* and *SHARE*. As fairness result is calculated from (3), we set inputs are generated randomly. Undoubtedly, it is meaningless for uncoordinated scheme calculation as random results would be calculated out. Uncoordinated scheme would not be employed for comparison.

For comparison between *SCHEME* and *SHARE*, networks' sets would be randomly generated, and number of coexistence networks also would vary from 2 to 20. And for *SHARE* simulation, we utilized the value $\alpha = 0.9$ and $r = 1.95$ from [11], [12]. Then, both these two mechanisms could satisfy ordinary fairness index $\frac{S_i}{S_j} = \frac{R_i}{R_j}$, but for a more simple and precise fairness calculation (3), the comparison result is shown in Fig.3. Obviously, *SCHEME* performance is better.

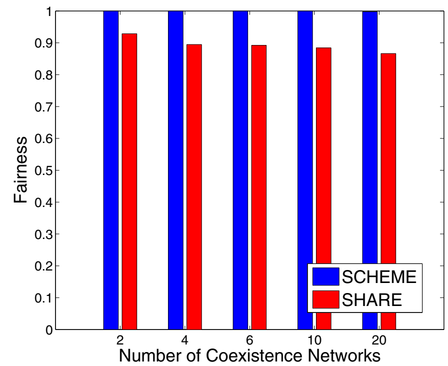


Fig. 3: Comparison

VI. CONCLUSION

We presented a *ecological Species Competition based HEterogeneous networks coexistence MEchanism* (*SCHEME*) in this paper to coexist heterogeneous CR networks in TVWSs, which is inspired by *SHARE* [11], [12]. *SCHEME* employed IEEE 802.19.1 as mediator to structure indirect coordination mechanism. And *SCHEME* adopts an algorithm which enable each coexistence network autonomously complete spectrum sharing allocation tasks: 1) dynamically adjust its own spectrum bandwidth according to QoS requirements, and 2) compete with other networks to achieve a fairness equilibrium. Analytical and simulation results showed out that *SCHEME* can converge to a stable and fairness optimum equilibrium.

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