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A Cell Based Dynamic Spectrum Management Scheme with Interference Mitigation for Cognitive Networks

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Abstract Future wireless systems are expected to be characterized by the coexistence of different *radio access technologies* (RATs) resulting in complex heterogeneous wireless environments. In parallel with this, the tremendous demand for spectrum has inspired the requirement of *dynamic spectrum management* (DSM). This paper aims at designing a *cell based dynamic spectrum management* (CBDSM) scheme to enhance the spectrum utilization and maximize the profit of operators in wireless heterogeneous networks. The system architecture and the functional modules supporting the CBDSM scheme are designed. As a fundamental issue in spectrum management, the inter-system interference issue is solved in the proposed CBDSM scheme. Furthermore, game theory, which is a potential tool for studying the distributed autonomous resource optimization algorithms, is applied to design a spectrum trading algorithm enabling the heterogeneous wireless networks to dynamically trade spectrum and to share the profit. In the algorithm, we take into account the economic value of the spectrum of wireless systems in order to guarantee the rationality for the spectrum trading. The simulation results show that the proposed CBDSM scheme effectively improves the spectrum utilization and the profit of operators while it reduces the mutual interference between wireless networks to a tolerable level.

Keywords Dynamic spectrum management · Game theory · Cognitive networks · Profit · Inter-system interference · Bargaining patience

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1 Introduction

The main features of future wireless communication systems are the heterogeneous RATs coexistence and the common IP core networks. These RATs have their own strengths and weaknesses in different aspects, such as system capacity, cost, quality of service (QoS), etc. Consequently, the convergence of heterogeneous networks has become a trend in research and regulation activities for future communication systems. In recent years, the cognitive concept [1] has been applied to the functional architecture, the resource management, and the network management aiming at realizing the convergence of heterogeneous RATs and bringing the full benefits of the valuable coexistence of heterogeneous RATs to users, operators, as well as application service providers.

The concept of *cognitive networks* (CN) [2–4] is to enable the wireless networks to have the capabilities of acquisition, cognition, strategy and execution in accordance with dynamic changes of wireless environments. These capabilities enable the self-adjustment in network management and realize autonomic communication systems. Considering these characteristics, CN is identified as a main developing trend of wireless communication. In order to support the evolution of heterogeneous networks towards CN, the need for reasonable resource management schemes to jointly optimize the heterogeneous resources arises. The resource management includes three issues, i.e. *dynamic network planning and management* (DNPM) [5], *dynamic spectrum management* (DSM) [5], and *joint radio resource management* (JRRM) [5]. Among these issues, DSM is a key approach dealing with joint resource management in a medium time scale. The objectives of DSM are to optimize the spectrum utilization, system capacity, as well as other network performances. Currently, the main branch of DSM research focuses on spectrum [6,7] for cognitive radios, enabling unlicensed users to check the spectrum holes and use them to transmit data. Another branch of DSM research deals with the spectrum management for heterogeneous RATs scenarios [8–11], in which RATs have their spectrum license and they are operated by specific operators. DSM for heterogeneous RATs scenarios is a very promising approach to help operators to meet the rising demand of users for high speed and broadband services. To date, the studies on DSM for heterogeneous RATs scenarios include the discussions on the DSM concept, the network architecture, the regulation and the roadmap towards DSM. However, concrete DSM schemes, which jointly consider the economic and technical aspects, are less emphasized and lacking in practical system architectures, functional architectures as well as detailed algorithms.

The main purpose of this work is to design a CBDSM scheme based on market competition and cooperation principles to solve the spectrum management for heterogeneous RATs in multi-operators scenarios. Since these networks are operated by different operators, we assume that they are selfish and greedy. In this paper, we apply game theory, a potential tool to study distributed autonomous resource optimization algorithms, to investigate a win–win solution for dynamic spectrum trading between networks. In the algorithm, the spectrum value of wireless networks is taken into account in order to guarantee the rationality for spectrum trading. Furthermore, we design an inter-system interference mitigation method and the system architecture supporting CBDSM scheme. The simulation results show that the CBDSM scheme optimizes the spectrum utilization and maximizes the operator's profit while effectively restricting the interference brought by DSM to a tolerable level.

The remainder of this paper is organized as follows. We begin in Sect. 2 by introducing the DSM related works. Section 3 proposes the overview of the system architecture and the related concepts, while the inter-system interference mitigation model is introduced in Sect. 4.

We present the spectrum trading model of the CBDSM scheme in Sect. 5. The simulation results and performance evaluation for the proposed CBDSM scheme is carried out in Sect. 6. Finally, Sect. 7 concludes the paper.

2 Related Works

Considering the scarcity and high economic value of spectrum, many recent researches on wireless communication technologies have focused on DSM issue. DSM is also a key feature in many research projects, such as DRiVE (*Dynamic Radio for IP-Services in Vehicular Environments*) [12], E^{2}R (*End-to-end Reconfigurability*) [13] and E3 (*End-to-end Efficiency*) [14]. Due to the development of reconfigurable hardware technology, the application of DSM to heterogeneous networks is becoming more and more realizable.

The analysis and results of spectrum measurement [15,16] show that the spectrum utilization is low in many spectrum bands. To enhance the spectrum utilization, the concept of DSM has been introduced and the benefit brought by DSM has been studied for overlapped heterogeneous RATs environments [7,8]. DSM effectively exploits the variant demands for spectrum in both spatial and time dimensions in different networks. Therefore, DSM improves the spectrum utilization compared to the traditional *Fixed Spectrum Management* (FSM). However, the implementation of DSM in real wireless systems requires the support from many related fields, including technical, business and regulatory aspects [10,11].

In [6] and [17], models for spectrum trading have been presented to realize the spectrum auction between a primary user and unlicensed users. In the models, a secondary spectrum market has been developed enabling unlicensed users to buy spectrum from the primary user. An opportunistic spectrum access mechanism has been designed [18,19] to help unlicensed users to dynamically use the spectrum of primary users. In this mechanism, unlicensed users monitor the control channel of the primary user to detect the idle time slots so as to transmit data. However, those approaches were meant to address a branch of DSM issue that is spectrum sharing between unlicensed users and primary users. The heterogeneous RATs scenarios are different with the above spectrum sharing scenarios in various aspects, such as system architecture and resource management. Therefore, the above approaches are not appropriate for DSM in heterogeneous RATs.

In [10,11], the preliminary analysis of network architecture has been studied to support DSM in heterogeneous RATs. This network architecture divides the whole overlapped area into many different sub-areas, which are called DSM areas. The main objective is to realize the flexibility and low complexity in spectrum allocation policies in each DSM area. In [20], a heuristic DSM scheme has been designed for heterogeneous DVB-T/UMTS systems. Nevertheless, this is a heuristic mechanism without concrete algorithms. In [21], a discrete time markov chain based DSM scheme has been developed for two wireless communication systems, such as single-cell *cellular network* and a single-cell *wireless metropolitan area network* (WMAN). In this model, the spectrum resource belongs to a centralized entity, which is responsible for allocating spectrum to the two networks according to their spectrum demand. In [22,23] spectrum auction schemes have been proposed for heterogeneous RATs scenarios, in which spectrum renters bid for each *spectrum trading unit* (STU) of spectrum leasers. Although the above papers discussed DSM for heterogeneous RATs, they only considered single-cell networks. But in the real world we have multiple-cell networks where inter-system interference brought by DSM plays an important role. Therefore, these approaches too can not deal with the DSM for heterogeneous RATs in practical networks.

Based on the above analysis, it is vivid that those papers did not consider the practical system architecture, functional architecture as well as concrete algorithms. Furthermore, little research effort focused on the inter-system interference, which is considered as a fundamental issue for applying DSM to the heterogeneous RATs systems. Consequently, how to design a reasonable DSM scheme which considers the practical network architecture, the detailed algorithm as well as the effective inter-system interference mitigation method for heterogeneous RATs remains a great challenge.

3 System Architecture

The system architecture of CBDSM is shown in Fig. 1, in which heterogeneous RATs, such as *global system for mobile communications* (GSM), *universal mobile telecommunications system* (UMTS), and *digital video broadcast terrestrial* (DVB-T), co-exist in an area. In the system architecture, we designed several functional modules to support the CBDSM scheme.

The spectrum market, which is shown in Fig. 1, originates from the concept of the real market. The spectrum market is a logical spot where RAT cells could fulfill the spectrum transaction with the others. In the spectrum market, RAT cells, which have spare spectrum owing to the low traffic, could lease out the spare spectrum to maximize their profit and their spectrum utilization. In contrast, if RAT cells are in need of spectrum, they could rent spectrum from the spare ones. The RAT cells, which rent spectrum, are called renting RAT cells while the RAT cells, which lease out spectrum, are called leasing RAT cells. Therefore, the spectrum market includes leasing RAT cells as the sellers, renting RAT cells as the consumers, and spectrum as the goods for transactions.

Indeed, the spectrum demand of RAT cells varies over time and space due to the dynamic nature of the traffic in RAT cells. In our CBDSM scheme, each RAT cell has a traffic estimator (TE) module, which is responsible for load prediction within its cell. There are many load prediction algorithms that could be adopted for TEs, such as current value prediction, linear regression prediction with n past samples, exponential regression prediction with n past samples, etc [8]. Before initiating the spectrum trading, each TE collects the past load samples of its RAT cell, and run the prediction algorithm to obtain the load estimation for the next time period. The past load samples could be collected by interacting with the entities

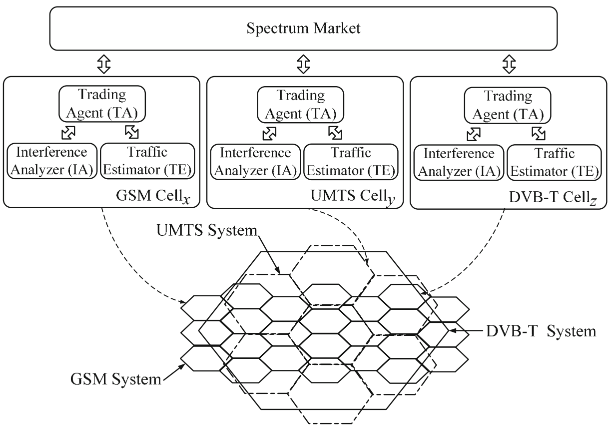

Fig. 1 CBDSM system architecture

responsible for the radio resource management of the RAT cell. The load prediction output in the TE of a RAT cell is sent to the trading agent (TA) of that RAT cell for further spectrum management processes.

The spectrum trading brings with it extra inter-system interference for wireless networks. In order to guarantee the interference performance, we design an interference analyzer (IA) module in each RAT cell to evaluate the interference brought by the spectrum trading. To accomplish this task, IA interacts with the corresponding TA to obtain the necessary information for interference analysis. The interference evaluation output in the IA of a RAT cell is sent to the TA of that RAT cell to help the TA to generate the decision whether the interference level brought by the spectrum trading is tolerable for that RAT cell.

Finally, to accomplish the spectrum trading, we design in each RAT cell a TA module responsible for strategy generation and trading negotiation. Each TA observes the spectrum market in order to obtain the spectrum trading information. It also interacts with the corresponding TE and IA modules for the traffic information and the interference evaluation results. Furthermore, TA makes a series of decisions related to the spectrum trading, such as how much spectrum it should rent or lease, which spectrum portion to be rented or leased, from whom to rent spectrum, to whom to lease spectrum. The spectrum trading is finally fulfilled through the negotiation among the TAs.

The load estimation in our CBDSM scheme is the estimation of average traffic in the future time period based on the past traffic samples. This approach is called imperfect load prediction [8]. Due to this imperfect information, there is imprecision in traffic estimation results compared to practical traffic situation. If leasing RAT cells lease out spectrum for a long period of time, they may not have enough spectrum when their practical load increases. For renting RAT cells, the spectrum rented from leasing RAT cells becomes useless when their practical load decreases. Hence, from the technical perspective, it is risky for both renting RAT cells and leasing RAT cells when they rent or lease out spectrum for a long period of time. Moreover, as spectrum demand of RAT cells varies over time, the supply and demand relationship in the spectrum market always changes. Similar to the real market situation, due to this changing supply and demand relationship, both renting RAT cells and leasing RAT cells are not wiling to rent or lease out spectrum for a long period of time. Therefore, from both technical perspective and economic perspective, the DSM period should be for a short term in order to decrease the risks in spectrum trading.

As mentioned in [8,9], the spectrum trading should be carried out periodically. Supposed that the DSM period is T, then the set of time for spectrum trading is $\tau = \{\tau_1, \tau_2, \dots \tau_n, \tau_{n+1} \dots\}$, in which the time interval between τ_n and τ_{n+1} is T. If a renting RAT cell rents a piece of spectrum for the (τ_{n+1}, τ_{n+2}) time period, it could use the spectrum portion to provide services in that time period. However, the spectrum portion should be returned to the leasing RAT cells at the end of the (τ_{n+1}, τ_{n+2}) time period [8,9].

With respect to traffic demand, networks with different application characteristics are expected to have different traffic at different time periods. This happens in heterogeneous wireless networks. For example, DVB-T is different with GSM and/or UMTS in service application aspect. Besides, in the CBDSM scheme, different networks are operated by different operators, thus the spectrum resources that the regulator allocates to them are different. This leads to the great differences in capacity of these networks. In fact, DVB-T network has abundant spectrum resource, while GSM/UMTS network has limited spectrum resource at most time. Therefore, the spectrum trading better utilizes the differences in both spectrum demand and capacity of heterogeneous networks in time and space dimensions to optimize the spectrum utilization and the operator's profit.

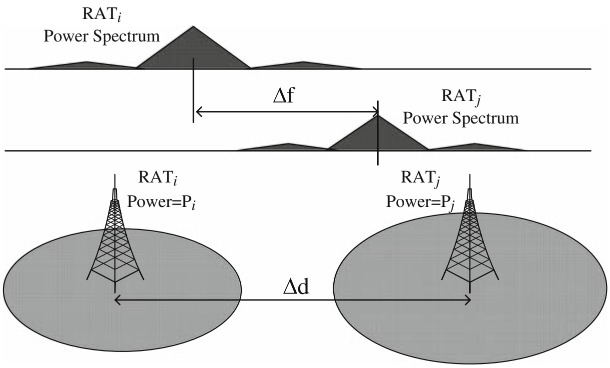

Fig. 2 Inter-system interference

4 CBDSM Interference Mitigation

4.1 Inter-System Interference

Beside the well known intra-system inference and thermal noise in wireless networks DSM creates an extra interference known as the inter-system interference. Figure 2 shows the inter system interference between two single-channel RAT cells. To simplify the expression, in this part, we use RAT$_i$ to RAT$_j$ to represent two cells of two different RATs.

The interference level between the two cells depends on their transmission power, their power spectrum density characteristic, the interval between the frequencies of the two channels, and the distance between the two antennas. Suppose that the distance between the two antennas of RAT$_i$ and RAT$_j$ is Δd and the interval between the frequencies of the two channels is Δf, then the distance Δd and interval Δf should satisfy specific constraints in order to guarantee an acceptable mutual interference level for the two cells as shown by the two equalities below.

$$\phi_{ij}(\Delta f, P_i, P_j) \leq \Delta d_{ij} \tag{1}$$

$$\phi_{ji}(\Delta f, P_j, P_i) \leq \Delta d_{ji} \tag{2}$$

In (1) and (2), Pi and P_j are the maximum transmission power of the two antennas. The constraint functions, ϕ_{ij} and ϕ_{ji}, are different depending on the characteristic of the RAT$_j$ and RAT$_i$. The first inequality is to mitigate the interference from RAT$_j$ to RAT$_i$ while the second inequality is to mitigate the interference from RAT$_i$ to RAT$_j$. These constraint functions are assumed to be known by IAs.

In order to guarantee an acceptable mutual interference level between the two cells, a minimum distance between the two antennas must be maintained which is calculated by the IAs as shown in (3) assuming that the transmission power and the frequency of RAT$_i$ and RAT$_j$ are given.

$$\Delta d_{min} = max \left\{\Delta d_{ij}, \Delta d_{ji}\right\} \tag{3}$$

In multi-channels scenarios, IAs should analyze all channel pairs of the two systems. IAs could obtain the minimum distance Δd_{min} between the two antennas for each channel pair, composing a Δd_{min} set. To guarantee the interference performance for the cells, the minimum distance should be satisfied for all of the channel pairs. Thus, the final minimum distance between the two cells in multi-channels scenarios should be the maximum value of the Δd_{min} set.

4.2 CBDSM Interference Mitigation

To guarantee an acceptable mutual interference level for the leasing side and the renting side in the spectrum trading, the leasing side probably needs to release spectrum in several cells. As shown in Fig. 3, when the cell$_x$ of RAT$_j$ rents a piece of spectrum from RAT$_i$, a set of cells in RAT$_i$, i.e. {Cell$_k$: $k = 6, 7, 8, 10, 11, 12, 13, 16, 17$}, have to release the spectrum. Thus, the spectrum trading does not just occur between a renting TA and a leasing TA, but between a renting TA and a set of leasing TA. If some of the cells can not release their spectrum due to its high traffic, the spectrum trading will be rejected as the mutual interference of the renting RAT cell and the leasing RAT cells does not satisfy the requirement.

Note that renting requests from a renting TA should contain the planned transmission power and geographical position of their antennas. Hence, all RAT cells are supposed to have *geographical information system* (GIS) equipment so as to know their position information. This position information and power information enables the leasing TAs to verify the minimum distance between the renting RAT cell and the leasing RAT cells. By this mechanism, it can control the interferences between the renting RAT cells and the leasing RAT cells.

The constraint functions affect the amount of TAs in the leasing TA set. These constraint functions depend on the interference level requirements. If the interference requirements are strict, the mutual interference will be slight for both renting sides and leasing sides. However, the amount of TAs that need to release the spectrum probably grows up. Therefore, the strict requirements of interference lead to a relatively poorer enhancement of both the spectrum utilization and the operator's profit. On the contrary, the loose interference requirements, which cause high mutual inter-system interference, can more greatly improve the spectrum utilization and the profit of operators.

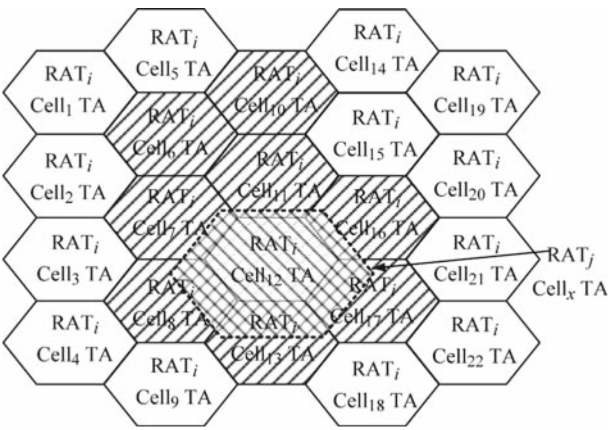

Fig. 3 CBDSM interference mitigation method

5 Spectrum Trading Scheme

5.1 Trading Model

In game theory, all players coordinate their actions for the purpose of furthering their own interest, but no one sacrifice their interest for the sake of the others. This is why game theory could be applied to solve the competition and cooperation relationship among wireless networks operated by different operators. From the aspect of renting sides, they rent spectrum for both maximizing their profit and enhancing their system capacity. From the aspect of leasing sides, they lease out the unused spectrum for enhancing their own network profit. Through the spectrum trading, both leasing sides and renting sides could earn profit. Due to this economic-driven aspect, both renting sides and leasing sides have a strong incentive to participate in the spectrum trading.

If the leasing TA set can meet the interference requirement for the spectrum trading with the renting TA, then both sides will negotiate with each other to reach an agreement for the spectrum trading. The negotiation between the renting TA and the leasing TA set can be considered as a dynamic game with complete information [23]. In our CBDSM scheme, we adopt *Rubinstein-Stahl* (R-S) [24,25] bargaining game for the negotiation model between the renting TA and the leasing TA set.

Suppose that the renting TA needs to rent S (Hertz) from the leasing TA set, then the renting TA could use that spectrum portion to deliver services to users and obtain profit. We define P_S as the profit that the renting TA gains from service provisions by using that spectrum portion. Since that spectrum portion is rented from the leasing TA set, the profit P_S should be shared with the leasing TA set. Therefore, the renting TA and leasing TA set have to negotiate with each other to reach an agreement for the profit sharing. The negotiation is considered as a bargaining process between the renting TA and the leasing TA set, which are also called two players of the bargaining game. The negotiation model is shown in Fig. 4.

Considering P_S as a "cake" of size 1, the two players will bargain over the division of the cake. The set of the possible agreement is

$$X = \left\{(x_{\mathrm{R}}, x_{\mathrm{L}}) \in \mathrm{R}^2 : x_{\mathrm{R}} \geq 0, x_{\mathrm{L}} \geq 0 \text{ and } x_{\mathrm{R}} + x_{\mathrm{L}} = 1\right\}, \tag{4}$$

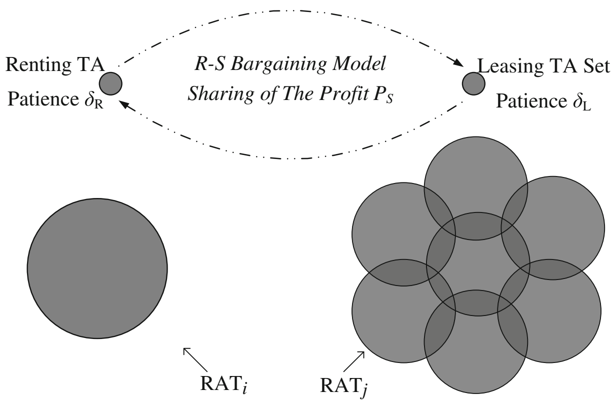

Fig. 4 CBDSM negotiation model

where x_{R} and x_{L} are the proportion of the cake divided for the renting side and the leasing side respectively.

As the players belong to wireless networks operated by different operators, they are greedy and selfish. The players try to get as much proportion of the cake as possible in the bargaining game. Their utility functions are the proportion of the cake assigned to them in the game. Let $u_{\mathrm{R}}(.)$ and $u_{\mathrm{L}}(.)$ denote the utility functions of the renting side and the leasing side respectively, then these utility functions are expressed as bellows.

$$u_{\mathrm{R}}(x_{\mathrm{R}}) = x_{\mathrm{R}} P_S \tag{5}$$

$$u_{\mathrm{L}}(x_{\mathrm{L}}) = x_{\mathrm{L}} P_S \tag{6}$$

In this R-S bargaining game, the players are supposed to have finite patience. In other words, players are impatient, thus the game is called impatient bargaining game. As mentioned in researches on R-S game [24,25], each player has a patience factor, also called discount factor, representing their patience level. We denote δ_R and δ_L as the patience factor of the renting side and the leasing side respectively. In the game, the more patient the player is, the larger piece of the cake they get. Due to the impatience of the players, there should be a final agreement accepted by both sides in the negotiation.

The bargaining process is as follows. The players can take actions only at times in the infinite set $N = \{1, 2, 3, \ldots n \ldots\}$. In the time of the set $n \in N$, one of the players, say i, proposes an agreement $(x_R^n, x_L^n) \in X$, and the other player, say j, either accepts the agreement or rejects it. If the offer is accepted, then the bargaining ends, and the agreement is implemented. If the offer is rejected, then the play passes to the next period, i.e. $n+1$ period. In this $n + 1$ period, player j incurs a discount on his utility and proposes an agreement $(x_R^{n+1}, x_L^{n+1}) \in X$, which player i can accept or reject. The game continues in this manner until one of the players accepts the agreement from another player. There is no limit on the number of the round. The *subgame perfect equilibrium* [24,25] for this game is defined by the agreement $x^* = (x_R^*, x_L^*)$ and the agreement $y^* = (y_R^*, y_L^*)$ that satisfies the following conditions.

$$u_{\mathrm{R}}(y_{\mathrm{R}}^*) = \delta_{\mathrm{R}} \cdot u_{\mathrm{R}}(x_{\mathrm{R}}^*) \tag{7}$$

$$u_{\mathrm{L}}(x_{\mathrm{L}}^*) = \delta_{\mathrm{L}} \cdot u_{\mathrm{L}}(y_{\mathrm{L}}^*) \tag{8}$$

This means that the renting side proposes agreement $x^*$and accepts any agreement that is at least y^* while leasing side proposes agreement $y^*$and accepts any agreement that is at least x^*. Note that $x^* \in X$ and $y^* \in$ X, thus the following two equations are also needed to be satisfied at the equilibrium.

$$x_{\mathrm{L}}^* = 1 - x_{\mathrm{R}}^* \tag{9}$$

$$y_{\mathrm{L}}^* = 1 - y_{\mathrm{R}}^* \tag{10}$$

From (5) to (10), we could obtain the subgame perfect equilibrium as below.

$$x^* = \left(\frac{1 - \delta_{\mathrm{L}}}{1 - \delta_{\mathrm{R}}\delta_{\mathrm{L}}}, \frac{\delta_{\mathrm{L}}(1 - \delta_{\mathrm{R}})}{1 - \delta_{\mathrm{R}}\delta_{\mathrm{L}}} \right) \tag{11}$$

$$y^* = \left(\frac{\delta_{\mathrm{R}}(1 - \delta_{\mathrm{L}})}{1 - \delta_{\mathrm{R}}\delta_{\mathrm{L}}}, \frac{1 - \delta_{\mathrm{R}}}{1 - \delta_{\mathrm{R}}\delta_{\mathrm{L}}} \right) \tag{12}$$

The final agreement should be x^* or y^* depending on who takes the final action. As in the real market situation, in R-S bargaining model, the leasing side is considered as the player who takes the final action that accepts or rejects the agreement from the renting side. Therefore, the final proportion that both players accept for the game should be x^*.

5.2 Bargaining Patience

The patience affects the negotiation results of both sides. Similar to the real market, the patience is constraint to the value of that spectrum portion to them. However, since RAT cells obtain profit from delivering services to users, the value of a spectrum portion to the renting side and the leasing side varies depending on their traffic. As a result, their patience changes over time. In addition, the patience should be nonsymmetrical for the renting side and the leasing side.

5.2.1 Spectrum Value

In order to participate in spectrum trading, RAT cells need to evaluate the traffic, and then evaluate their spectrum value. The traffic estimation and the spectrum value estimation are accomplished by TEs. The spectrum value of a RAT cell depends on the traffic within its cell. Assumed a RAT cell with total spectrum of B, then a spectrum portion S will have an estimated value as follows

$$V^S = \frac{L\alpha}{B} S, \tag{13}$$

where L is the estimated traffic, and α is the profit per unit traffic.

5.2.2 Renting Side Patience

In the renting side, the spectrum value expresses the demand for spectrum. If the spectrum value of a RAT cell grows up, it predicates that the RAT cell can get more profit through service provisions. Obviously, the RAT cell greatly needs spectrum to provide services and enhance profit. As a result, it lacks patience in the bargaining game. Thus, the renting side patience is a decreasing function of its spectrum value. Moreover, in R-S bargaining model, the patience is from zero to one. Therefore, we can define the conditions for patience function of the renting side as follows

$$\frac{d\delta_{\mathrm{R}}(V^S_{\mathrm{Rent}})}{dV^S_{\mathrm{Rent}}} < 0, \delta_{\mathrm{R}}(0) = 1, \delta_{\mathrm{R}}(\infty) = 0, \tag{14}$$

where V^S_{Rent} is the value of the spectrum portion of the renting side, and S is the bandwidth of the spectrum portion it needs to rent.

Any function that satisfies the above conditions could be the patience function of the renting side. In this paper, we adopted the following function for the renting side patience [26]

$$\delta_{\mathrm{R}}(x) = 1 - \frac{e^{\mu x} - e^{-\mu x}}{e^{\mu x} + e^{-\mu x}}, \tag{15}$$

where μ is a renting patience (RP) coefficient.

5.2.3 Leasing Side Patience

The leasing side is a set of TAs, which need to release the spectrum for the renting side. Each TA of the leasing side has their own estimated value of the spectrum portion to be released in the spectrum trading. The spectrum value of the leasing side is the sum of the spectrum value of all the TAs, which need to release spectrum.

If the leasing side has high spectrum value, it will expect to obtain more proportion of the "cake" in the bargaining game. Therefore, it will be more patient in the negotiation. The leasing side patience is an increasing function of its spectrum value. Moreover, the patience is from zero to one in R-S model. Thus, the conditions of the patience function of the leasing side are

$$\frac{d\delta_{\mathrm{L}}(V_{\mathrm{Lease}}^{S})}{dV_{\mathrm{Lease}}^{S}} > 0, \delta_{\mathrm{L}}(0) = 0, \quad \delta_{\mathrm{L}}(\infty) = 1, \tag{16}$$

where V_{Lease}^{S} is the value of the spectrum portion of the leasing side and S is the bandwidth of the spectrum portion to be released.

Any function that satisfies the above conditions could be the patience function for the leasing side. The function we adopted in this paper is [26]

$$\delta_{\mathrm{L}}(x) = \frac{e^{\lambda x} - e^{-\lambda x}}{e^{\lambda x} + e^{-\lambda x}}, \tag{17}$$

where λ is a leasing patience (LP) coefficient.

5.3 DSM Profit Sharing

As discussed in the trading model, after several rounds of bargaining, both sides will finally come to an agreement. This agreement is x^*. The profit P_S that the renting side gets from users by delivering wireless services to them should be shared between the renting side and the leasing side. The final profit obtained by each player is equivalent to its utility function, which is represented by the equations below.

$$u_{\mathrm{R}}(x_{\mathrm{R}}^*) = \left(\frac{1-\delta_{\mathrm{L}}}{1-\delta_{\mathrm{R}}\delta_{\mathrm{L}}}\right) P_S \tag{18}$$

$$u_{\mathrm{L}}(x_{\mathrm{L}}^*) = \left(\frac{\delta_{\mathrm{L}}\,(1-\delta_{\mathrm{R}})}{1-\delta_{\mathrm{R}}\delta_{\mathrm{L}}}\right) P_S \tag{19}$$

Since our model is a complete information bargaining game and each player is having full access to all the necessary information needed to carry out the bargaining, each player calculates the final results at its own end. This would help to reduce signaling overhead as well as excessive workload of the bargaining process.

Furthermore, DSM profit sharing process is carried out immediately after DSM period has expired. This means that if the renting side rent spectrum for (τ_{n+1}, τ_{n+2}) time period, then when the time τ_{n+2} comes, the renting side will pay for the leasing side the profit equivalent to the utility function of the leasing side as expressed in the Eq. 19. At the same time, the renting side should return the spectrum portion to the leasing side.

6 Simulation and Evaluation

6.1 Simulation Scenario

We assume an area overlapped by four RATs, in which GSM_1, GSM_2 and UMTS FDD include 14 cells, and DVB-T includes only 1 cell. The frequency reuse factor is 7 for the two GSM and 1 for UMTS while there is no frequency reuse in DVB-T as it has only one cell in the simulation scenario. The total spectrum bandwidth of the two GSM_1, GSM_2, UMTS

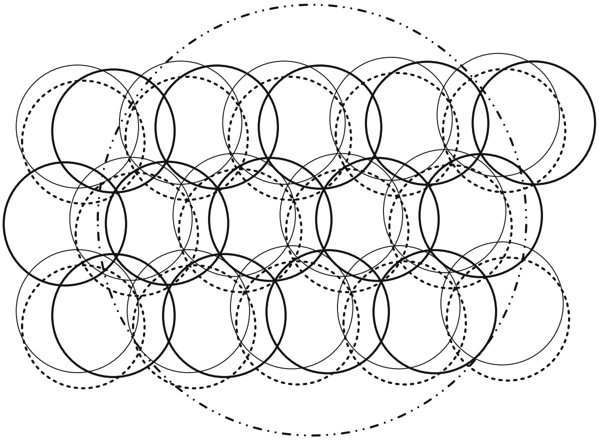

Fig. 5 Simulation network deployment

and DVB-T is 7, 7, 15 and 24 MHz respectively. The network deployment in the simulation scenario is shown in Fig. 5. The other simulation parameters are listed in Table 1.

For illustrative purpose, we compared the CBDSM scheme to FSM scheme in our simulation. The simulation was run for a day (24 h).

In this simulation, we investigated the spectrum utilization, the profit obtained by operators, as well as the interference performance in all the systems. Moreover, to evaluate the interference performance, we adopted the following path loss model, which is recommended in 3GPP 25.942 [27], in the simulation

$$Los(\text{dB}) = 15.3 + 36.7lg(d(\text{m})), \tag{20}$$

where d is the distance between the transmitter and the receiver in meters.

In addition, to simplify the simulation, we assume that all the cells of a homogeneous network have the same transmission power. If the transmission power is different, the simulation could be done similarly. Moreover, the spectrum masks applied in our study are specified in 3GPP 05.05 [28], 3GPP 25.104 [29] and ETSI EN 302 [30] for GSM system, UMTS FDD system and DVB-T system respectively.

Table 1 Simulation parameters

Parameters	GSM_1	GSM_2	UMTS	DVB-T
Transmission power (dBm)	43	43	43	60
Cell radius (m)	577	577	577	1750
Channel bandwidth B (MHz)	0.2	0.2	5	8
Unit traffic load profit α	2	2	3	1
RP coefficient μ	1			
LP coefficient λ	5			
Temperature (K)	290			
Noise factor (dB)	4			
Antenna gain (dB)	4			
DSM time period T (min)	30			

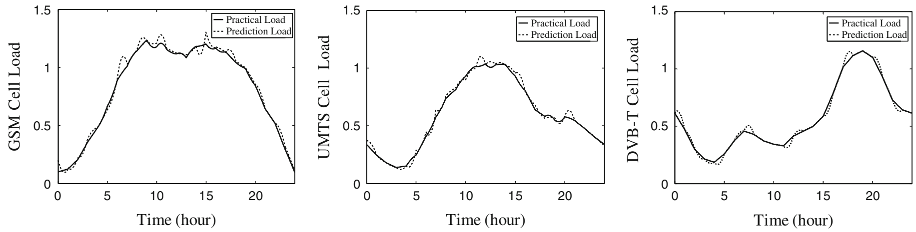

Fig. 6 Cell estimated and practical load: (**a**) GSM, (**b**) UMTS and (**c**) DVB-T

In order to fulfill the spectrum trading, TEs estimate their traffic to decide the amount of spectrum to be rented or leased. We adopted a prediction algorithm that combines history value prediction and linear regression prediction with two past samples [8]. Take one GSM cell and one UMTS cell as examples, the estimated and practical load curves are shown in Fig. 6a and b. The practical load curves are based on the standard pattern of Almeida et al. [31], in which GSM traffic and UMTS traffic are low at night, but high during the day. The traffic of the cells belonging to a homogenous network is not the same due to the difference of the user number in the cells and the difference of user activity in the cells. In the simulation, the traffic of RAT cells is generated randomly at different time. In addition, the estimated and practical load of the DVB-T cell is shown in Fig. 6c. The load curve is similar to those seen for TV viewing from Kiefl [32], in which the load is low during the day, but high at night. In this respect, the load curve of DVB-T and the load curve of UMTS and GSM have an excellent complementary characteristic, which can help to improve the spectrum utilization.

6.2 Results and Evaluation

To evaluate the performance of the CBDSM scheme, firstly, we investigate the profit of GSM_1, GSM_2, UMTS and DVB-T as shown in Fig. 7a–d. The profit of each network is not the profit of individual RAT cell, but the total profit of all cells of that network. Moreover, the profit is from both service provisions and spectrum trading as below

$$P_{\text{RAT}} = P_{\text{Serv}} + P_{\text{DSM Lease}} - P_{\text{DSM Rent}}, \tag{21}$$

where P_{Serv} is the total profit that the network earns from providing services to users, $P_{\text{DSM Lease}}$ is the total profit that the network obtains by leasing spectrum, and $P_{\text{DSM Rent}}$ is the total profit that the network has to pay for renting spectrum.

Note that a homogenous network includes several cells. Since the spectrum resource and the traffic of these cells are different, some of the cells need to rent spectrum while some

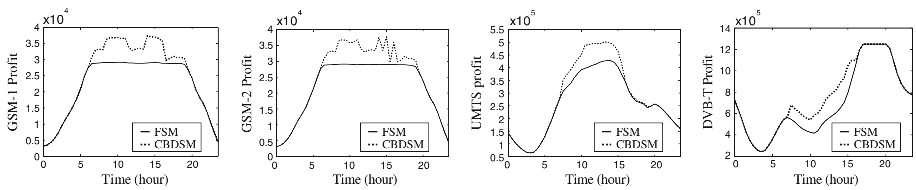

Fig. 7 Operator's profit: (**a**) GSM_1, (**b**) GSM_2, (**c**) UMTS and (**d**) DVB-T

others need to lease spectrum. As a result, each network probably includes both renting RAT cells and leasing RAT cells.

As shown in Fig. 7a–d, it is vivid that the CBDSM greatly enhances the profit of all networks. In the first 6 h and the last 6 h of the day, the traffic in all RAT cells is quite low, thus there is no opportunities for spectrum trading. As a result, the profit is the same in CBDSM and FSM. However, when the load in these networks increases, the profit differences are obvious. In the time period from 8th to 16th, where the traffic in GSM_1, GSM_2, and UMTS is high, many of the GSM cells and UMTS cells rent spectrum, resulting in great profit improvements for all networks.

In detailed, the CBDSM scheme creates an average profit improvement of 11%, 10%, 8%, and 5% for GSM_1, GSM_2, UMTS and DVB-T respectively compared to FSM scheme. Especially, in high load time periods, these improvements are significantly high, which are 30%, 30%, 25% and 42% respectively.

Secondly, we look into the interference performance in these systems. In this study, we simulated the C/I of each carrier at each position in all the systems. The distribution of C/I can illustrate the interference performance in these networks. Figure 8a–c show C/I distribution in GSM_1, GSM_2 and UMTS systems in both FSM scheme and CBDSM scheme.

As analyzed in previous parts, spectrum trading brings with it extra inter-systems interference for wireless networks. Nevertheless, the interference is mitigated by the constraint functions ϕ_{ij} set. As shown in Fig. 8a–c, though there is extra interference in the CBDSM scheme, the interference increment is slightly and does not affect the reliable communication in these networks.

In GSM_1 and GSM_2 networks, the interference performance is almost the same. In FSM, all the C/I in FSM is more than 20 dB. In CBDSM, 98.1% of C/I is more than 20 dB while 1.5% of C/I is lesser than 20 dB. This 1.5% of C/I takes the value from 11 dB to 20 dB in GSM_1 and from 12 dB to 20 dB in GSM_2. Since the minimum required C/I is 9 dB for GSM, the above C/I is large enough to guarantee the reliable communication for the two GSM networks. Generally, the distribution function of C/I in CBDSM is slightly more than that of FSM. This increment is not more than 2%.

In UMTS, the distribution of C/I is almost the same in CBDSM scheme and FSM scheme, especially in low C/I. This is because UMTS is a spreading spectrum system, which has high capability of anti-interference. In both CBDSM and FSM scheme, the minimum C/I is -6 dB. At C/I of more than -1 dB, distribution function of C/I in CBDSM scheme is slightly more than that of FSM scheme. The interference performance of the UMTS system is shown in Fig. 8c. Besides, as there is only one cell, DVB-T network will release the spectrum portion if it leases out to any renting sides. Therefore, the CBDSM scheme creates almost no interference increment to DVB-T network.

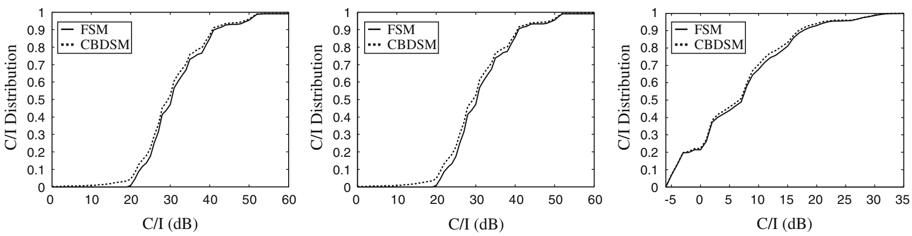

Fig. 8 C/I distribution function: (**a**) GSM_1, (**b**) GSM_2, and (**c**) UMTS

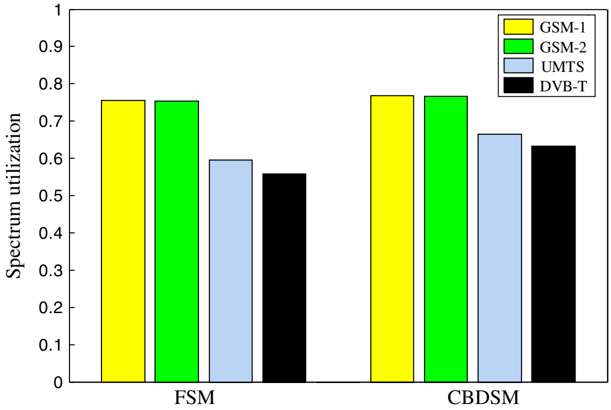

Fig. 9 Average spectrum utilization

Finally, we study the average spectrum utilization ratio in each network. The term "spectrum utilization ratio" here represents the ratio of the spectrum utilized to provide services to users and the total spectrum resource assigned to each RAT cell. Each RAT cell has different spectrum utilization ratio. Therefore, in the simulation, we analyze the average spectrum utilization ratio of all RAT cells of each system in the whole simulation time (i.e. 48 DSM periods). The meanings of the term "average" here are two-fold. First, it is the average value of the spectrum utilization ratio of all RAT cells belonging to that network. Second, it represents the average value of the spectrum utilization ratio of that network in all 48 DSM time periods. In other words, this average spectrum utilization ratio is the average value of the spectrum utilization ratio on both time dimension and space dimension.

The simulation results are represented in Fig. 9. In CBDSM scheme, the average spectrum utilization ratios of GSM_1, GSM_2, UMTS and DVB-T networks are 76.98%, 76.82%, 66.32%, and 63.41% respectively. In FSM scheme, these values are 75.53%, 75.53%, 59.69%, and 55.66% in GSM_1, GSM_2, UMTS and DVB-T respectively. Note that in a specific RAT cell and in a specific time, the spectrum utilization ratio could reach 100%. However, since the results shown in Fig. 9 are the average values of the spectrum utilization ratio, they never reach 100%. In the parameter configuration, similarly to the practical application situation, the traffic is set to a high level in both GSM networks, hence they rarely lease out spectrum for the other RAT cells. As a result, the spectrum utilization improvements are very slight, which are 1.45% 1.29% for GSM_1 and GSM_2. However, the spectrum utilization improvements are high for UMTS and DVB-T, which are 6.63% and 7.75% respectively. From the above analysis, it is vivid that CBDSM scheme is effective in enhancing the spectrum utilization ratio in heterogeneous wireless systems.

7 Conclusions

In this paper, we presented a CBDSM scheme for heterogeneous wireless networks enabling the self-adjustment capability in spectrum management. This work considered both system architecture design and detailed algorithm design. The system architecture and the functional modules have been proposed to support the CBDSM scheme. Moreover, we designed the inter-system interference mitigation method so as to guarantee an acceptable interference level for wireless networks. The spectrum trading algorithm based on the R-S bargaining game has been proposed enabling renting sides and leasing sides to trade spectrum and to bargain over the profit division. In the trading algorithm, the spectrum value of wireless systems has been considered so as to guarantee the rationality for the spectrum trading. The simulation results revealed that the CBDSM scheme not only improves the spectrum utilization and the profit of operator, but also effectively restrains the interference among wireless systems to an acceptable degree.

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Appendix: Acronyms Description

Acronyms	Description
CBDSM	Cell Based Dynamic Spectrum Management
CN	Cognitive Networks
DNPM	Dynamic Network Planning and Management
DRiVE	Dynamic Radio for IP-Services in Vehicular Environments
DSM	Dynamic Spectrum Management
DVB-T	Digital Video Broadcast Terrestrial
ETSI	European Telecommunications Standards Institute
E2R	End to End Reconfigurability
E3	End to End Efficiency
FDD	Frequency Division Duplex
FSM	Fixed Spectrum Management
GIS	Geographical Information System
GSM	Global System for Mobile Communications
IA	Interference Analyzer
IP	Internet Protocol
JRRM	Joint Radio Resource Management
RAT	Radio Access Technology
R-S	Rubinstein-Stahl
SDR	Software Defined Radio
STU	Spectrum Trading Unit
TA	Trading Agent
TE	Traffic Estimator
TV	Television
UMTS	Universal Mobile Telecommunications System
WMAN	Wireless Metropolitan Area Network
3GPP	Third Generation Partnership Project

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