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An Efficient Dynamic Spectrum and Distributed Resource Allocation in a Cognitive Digital Home

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ABSTRACT

Multi radio access technologies deployments of wireless communication systems provide communication services over different Radio Access Technologies transmitted from the same cell site over the same or different antennas. In a cognitive Digital home a framework for distributed resource allocation and admission control is used. For addressing the spectrum coexistence of legacy devices we consider two channel access models. One is Pessimistic Controllability (PC) Model where the Home Genie node (HG) has no influence over legacy devices. The second one is Switched RAT (SR) Model where the HG has perfect control of legacy devices. Distributed algorithms for maximizing sum rate and maximizing service capacity are designed using partial dual decomposition techniques.

In a cognitive digital home for the efficient use of energy, a distributed power control scheme is used. To enhance the system feasibility, an admission control technique based on pricing information obtained from the distributed algorithm is used. Further to improve the dynamism, we introduce a new technique called a cross layer opportunistic spectrum access and dynamic routing algorithm for cognitive radio networks is proposed, called ROSA (Routing and Spectrum Allocation algorithm). Through local control actions, ROSA aims at maximizing the network throughput by performing joint routing, dynamic spectrum allocation, scheduling, and transmit power control. Specifically, the algorithm dynamically allocates spectrum resources to maximize the capacity of links without generating harmful interference to other users while guaranteeing bounded BER for the receiver.

Keywords

Cognitive digital home, distributed resource allocation, admission control, power control, home genie node, multi-hop.

1. INTRODUCTION

The increasing demand in radio access technologies on heterogeneous data services, integration of wireless networks with multiple RATs is expected to be a prevalent feature of future mobile networks. With the arrival of cognitive and multi-platform radios, the spectrum occupancy of these devices and RATs to range from the TV white spaces (54MHz ~ 698MHz) , to unlicensed bands (2.4GHz and 5GHz) and even all the way to 60GHz radio bands in a digital home.

In a digital home the most important is the effective operation of multi-RAT networks, which is a framework for optimized dynamic usage of radio resources in wireless networks with multi-RATs and multi-operators.. A utility maximization problem for multi-channel, multi-RAT and multihop wireless networks and a dynamic algorithm was proposed based on the decomposition of this problem.

Fair and efficient resource allocation is important in supporting various data services. A framework is used for centralized spectrum management in a cognitive digital home (CDH) where a home genie node (HG) coordinates spectrum coexistence across a multiplicity of RATs. In a CDH, legacy RATs are allowed to exist and Cognitive Radio (CR) RATs can access all the spectral resources when they are available. These assumptions make our CDH model different in describing multi-RAT wireless home networks and also add much more complexity to the resource allocation problems within it. To consider two models in a CDH for addressing spectrum coexistence of legacy devices: (i) Pessimistic Controllability (PC) Model, and (ii) Switched RAT (SR) Model. In addition it helps to improve the dynamism and consider interactions between spectrum management and dynamic routing functionalities. We propose a distributed algorithm that jointly solves the routing, dynamic spectrum assignment, scheduling and power allocation problems for cognitive radio networks.

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2. BACKGROUND

2.1 Local Wireless Multimedia Access

The large variety of applications indicates that the wireless infrastructure should support real-time traffic with largely varying delay constraints as well as non-real-time traffic with different reliability requirements. Flexible network solutions are required to accommodate the large number of communicating devices. In particular, the flexibility requirement is prominent in ad hoc network architectures that have multi-hop capabilities with many different operators in the same areas. The significance of all this is that next to the network capacity required to accommodate the actual application, there is much additional transfer capacity needed for quality of service provisioning and key features such as dynamic resource allocation and routing and security protocols for data integrity and protection against unauthorized access.

An alternative method of increasing spectral efficiency is to exploit space by using multiple transmit and receive antennas and transmitting different data streams on the different transmit antennas simultaneously. Various approaches can be followed. One method, known as space-time coding, is to encode the data by a channel code and split the encoded data into a number of parallel streams that are simultaneously transmitted on the different transmit antennas. Another technique is to properly exploit multipath scattering by using an appropriate processing architecture. It has been demonstrated that in such a way bandwidth efficiencies of 20–40 b/s/Hz can be reached.

2.2 Spectrum and Radio Resource Management

Due to the rapid evolution of wireless technologies which allows operators to deliver more advanced multimedia services. High-speed packet access (HSPA) for uplink and downlink is seen as an intermediate evolutionary step since the first wave of wideband code division multiple access (WCDMA)-based networks rollout, while evolved universal mobile telecommunications system (UMTS) terrestrial radio access networks (E-UTRAN) are the long term perspective for the Third Generation Partnership Project (3GPP) technology family. Similar paths are drawn from the 3GPP2 around the evolution of code division multiple access 2000 (CDMA2000). Moreover, the IEEE 802 working groups are producing an evolving family of standards, such as 802.11 local, 802.15 personal, 802.16 and 802.20 metropolitan and 802.22 regional area networks.

This presents a framework to achieve an optimized dynamic spectrum and radio resource usage in heterogeneous wireless network and multi-operator scenarios. The envisaged technical solution follows a layered approach, where joint radio resource management (JRRM) and advanced spectrum management (ASM) mechanisms are identified at both intra- and inter-operator levels. The interaction between layers, together with reference operative time scales, is described and accompanied by an illustrative case study. Moreover, the importance of CN functionalities is highlighted as a key enabler. Finally, the different steps of the cognition cycle are further developed, with particular emphasis on guiding principles to be applied to the different stages.

2.3 Multi-Access Radio Network Environments

Emerging applications call for the vehicular networks to support multimedia and real-time services. It investigates relevant network selection approaches that have been adopted by widely accepted telecommunication standards and briefly presents recent research proposals of the literature. More specifically, the article introduces the decomposition of the network selection problem into four fundamental steps. The next generation of wireless systems represents a heterogeneous environment with different RATs that differ in bandwidth, latency, or cost. At the same time, portable devices, such as laptops, notebooks, or personal digital assistants, support multiple radio network interfaces. Moreover, demands of Internet connection at anytime and anywhere are increased. In this kind of environment, mobility management is the essential issue that supports the roaming of users from one system to another.

Selection of the most efficient and suitable access network to meet specific application's QoS requirements has become a significant topic and its actual focus is on maximizing the QoS experienced by the user. More specifically, the goal of this process is to aid the user/mobile terminal (MT) in connecting to the radio access network that will best serve the requested service—according to a series of metrics that may refer to technical characteristics, economic aspects, etc. Network selection is an important part of consumer-centric models for wireless access services. As the provision of seamless and context-aware services is required by future vehicular networks, this issue is of great interest to the vehicular communication society as well, to achieve a balance between the requirements of the V2I system and the minimization of the rollout and operational costs.

3. PROPOSED ARCHITECTURE

A distributed power control scheme is also designed for efficient use of energy. An admission control scheme based on pricing information obtained from the distributed algorithms is used to improve system feasibility.

Under the PC model whose preliminary results can be found in we assume that the HG is unable to exercise any control over the devices of legacy RATs and hence cannot influence how the resources are shared by legacy devices that share spectrum (see Figure 1).

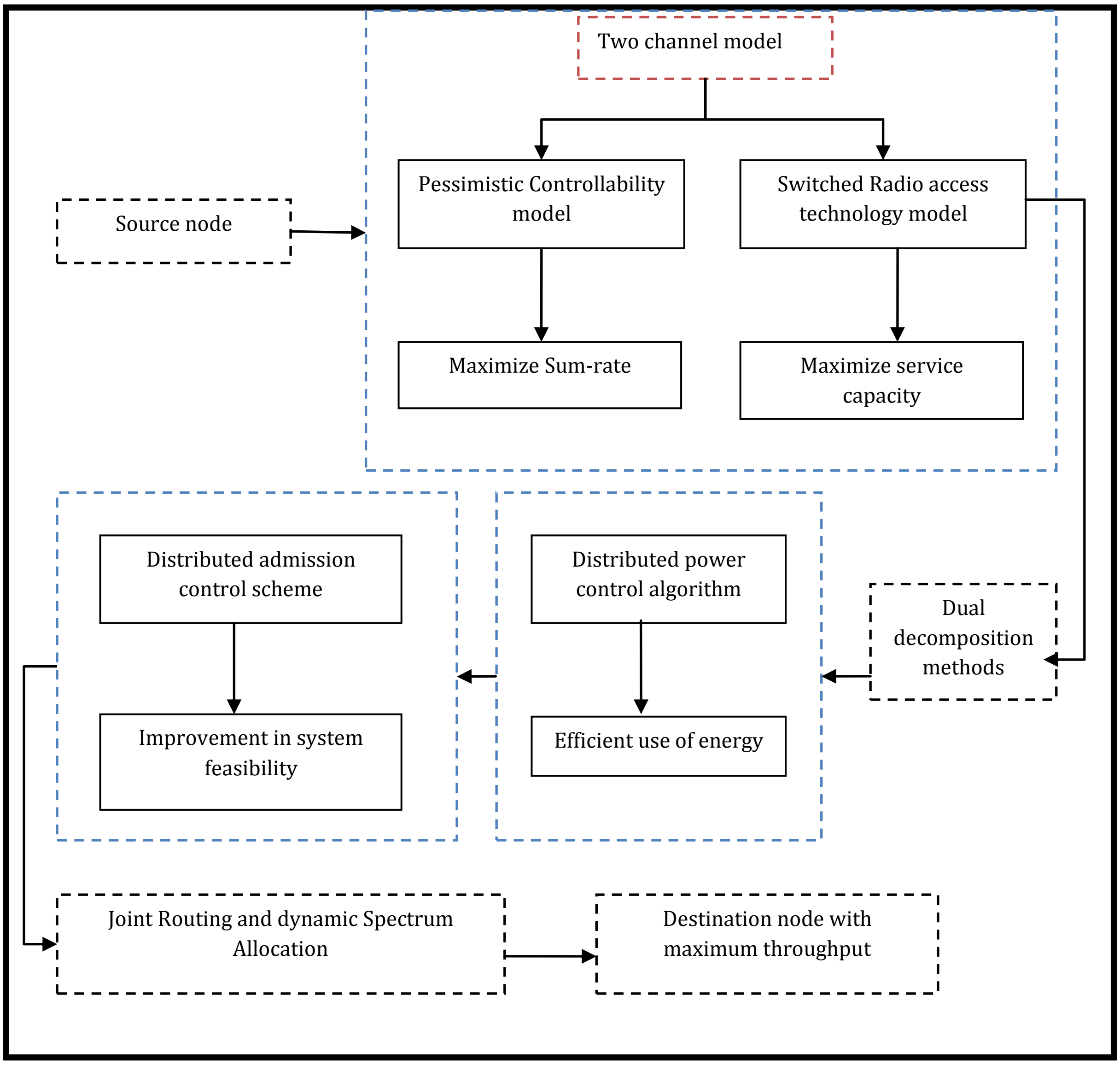

Fig 1: System architecture

4. DYNAMIC ALLOCATION OF SPECTRUM IN A COGNITIVE DIGITAL HOME

4.1 Description

Implementation is the process of converting a new or revised system design into an operational one when the initial design is done for the system. This process is used to verify and identify any logical malfunctioning of the system by feeding various combinations of test data. Implementation includes developing the identified modules and integrating them together so that the system functions efficiently and effectively. Proper implementation is essential to provide a reliable system to meet the requirements. The modules identified in the proposed system are:

4.1.1 Joint Channel and RAT Allocation

The resource allocation in a CDH includes the assignment to each service a set of channels, corresponding RATs along with choice of transmission power, modulation and coding scheme. In the Joint Channel and RAT Allocation (JCRA) problem, the first one is Maximizing Sum Rate (MSR), aims to maximize the sum rates while supporting all the inelastic services (rate constrained). By solving this problem, the network efficiency of the CDH can be maximized while the fairness among services can be guaranteed.

$$\max_{X,L} \sum_{k \in \mathcal{K}} \sum_{i \in M} \sum_{t \in T} R^{p}(k,i,t) l(k,i,t)$$

$$\sum_{i \in M} \sum_{t \in T} R^{p}(k,i,t) l(k,i,t) \geq R_k^{min}, \qquad \forall k \in \mathcal{K}$$

$$P(k,i,t) = P_t, \ \forall k \in \mathcal{K}, \forall_i \in M, \forall_t \in T$$

$$\sum_{i\epsilon M}\sum_{t\epsilon T} P(k,i,t)x(k,i,t) \leq P_k^{max}, \quad \forall k\epsilon \mathcal{K}$$

where **X** and **L** are matrices of control variables. The k-th row of **X** is X_k defined which indicates the channel usage of the k-th service over all the channels and RATs. That of **L** is l_k**l** describes the actual physical resource share of the k-th service over all the channels. For Maximizing Service Capacity (MSC) problem is formulated in order to support as many rate constrained services as possible.

$$\max_{X,L} \sum_{k\epsilon K} u\left(\sum_{i\epsilon M}\sum_{t\epsilon T} R^p(k,i,t)l(k,i,t) - R_k^{min}\right)$$

$$P(k,i,t) = P_t, \ \forall k \epsilon K, \forall i \epsilon M, \forall t \epsilon T$$

$$\sum_{i\epsilon M}\sum_{t\epsilon T} P(k,i,t)x(k,i,t) \leq P_k^{max}, \quad \forall k\epsilon K$$

Depending on which channel access model is used, i.e., PC model or SR model, the problems are named as PC-MSR, PC-MSC, SR-MSR and SRMSC.

4.1.2 Distributed Algorithms for PC-MSR and PC-MSC

In the PC-MSR problem, the minimal rate requirements and maximal transmit power requirements are all service-wise. Further, the RAT power constraint does not imply any coupling among the services. Thus, an intuitive idea is to decompose this problem service-wise by relaxing either or both into the objective function with the only constraint implying couplings among services being the channel usage constraints. For the PC-MSR problem, the major concern is to make the system feasible and thus relaxing individual rate requirements into the objective function is preferred. The partial dual function can be obtained by solving the following problem:

$$\max_{\{X,L\}\epsilon Q} \mathcal{L}(X,\lambda) = \sum_{k\epsilon K}\sum_{i\epsilon M}\sum_{t\epsilon T} R^p(k,i,t)l(k,i,t) + \sum_{k\epsilon K}\lambda_k\left(\sum_{i\epsilon M}\sum_{t\epsilon T} R^p(k,i,t)l(k,i,t) - R_k^{min}\right)$$

$$P(k,i,t) = P_t, \forall k\epsilon K, \forall i \epsilon M, \forall t \epsilon T$$

$$\sum_{i\epsilon M}\sum_{t\epsilon T} P(k.i.t)l(k,i,t) \leq P_k^{max}, \forall k\epsilon K$$

where Q is the feasible set and the constraints $\lambda_k \geq 0$, $\forall k \epsilon K$ is the Lagrangian multiplier and L(X,λ) is the Lagrangian function.

4.1.3 Distributed Algorithms for SR-MSR and SR-MSC

A two stage Distributed algorithm for the SR-MSR and SR-MSC problems that we refer to as DSRM is designed as follows. In the first stage of the D-SRM, an initial channel and RAT allocation should be obtained in a distributed manner. (i)D-PCM will output an initial channel and RAT allocation efficiently, and (ii)D-PCM is distributed where the majority of the computation and sensing burden is assigned to the services. Thus, the D-PCM becomes a proper subroutine candidate here. In the second stage, with the initial channel and RAT allocation, i.e., $\hat{X}$, the HG solves a simple linear program (LP) to refine the resource allocation on the channels with legacy RATs to determine the exact portion of the physical resources each service will obtain. The legacy RATs refinement LP can be formulated as:

$$\max_{L} \sum_{k\epsilon K}\sum_{i\epsilon M}\sum_{t\neq CR} R^p(k,i,t)l(k,i,t)$$

$$\sum_{i\epsilon M}\sum_{t\neq CR} R^p(k,i,t)l(k,i,t) \geq R_k^{res}, \quad \forall k\epsilon K$$

$$\sum_{k\epsilon K}\sum_{t\neq CR} l(k,i,t) = 1, \quad \forall i\epsilon M$$

$$0 \leq l(k,i,t) \leq \hat{x}(k,i,t), \quad \forall k\epsilon K, \quad \forall i\epsilon M,$$

The initial allocation $\hat{X}$ results in a feasible allocation. Thus, no power constraint is required here. Meanwhile, only the services assigned with legacy RAT on a channel in $\hat{X}$ can be further considered for allocation on that channel.

4.1.4 Power Control Scheme

The joint channel and RAT allocation itself is already *NP*-complete. Adding power control as an additional degree of control, i.e., joint channel, RAT and power allocation, will make the problem even more intractable. To overcome the intractability, we propose power control in a CDH as an additional functionality which can improve the system performance based on the allocation results from D-PCM or D-SRM algorithms. Given the channel and RAT allocation result obtained from D-PCM or D-SRM, i.e, X^* and L^* the power control can be implemented locally by each service as follows:

$$\max_{P_k} \sum_{i\epsilon M}\sum_{t\epsilon T} R^p(k,i,t)l^*(k,i,t)$$

$$\sum_{i\epsilon M}\sum_{t\epsilon T} P(k,i,t)x^*(k,i,t) \leq P_k^{max}$$

$$0 \leq P(k,i,t) \leq P_t^{max}, \quad \forall i \epsilon M, \forall t \epsilon T,$$

where each service tries to locally maximize its achieved data rates given the channel and RAT assignment.

4.1.5 Power Control Scheme

The JCRA problems, e.g., PC-MSR and SR-MSR, are all NP-hard and thus their feasibility is hard to achieve. The JCRA problems in a CDH are in general nonlinear. Therefore, specific admission control methods should be developed to address the infeasibility issue. The pricing indices PI_k used in resource allocation provide a nice indication for admission control since they represent the gap between each service's target data rate and its achievable data rate in the resource claim iteration. The Average Pricing Index scheme rejects the service with the largest average pricing index k= arg $\max_{i\epsilon k} \widehat{PI_i}$ = arg $\max_{i\epsilon K} \frac{\sum_{itr=1}^{MaxItr} PI_i(itr)}{MAxItr}$.

where MaxItr is the maximum number of resource claim iterations before the system is determined infeasible. The API scheme will reject the services until the remaining system is determined feasible by either D-PCM or D-SRM or all the services are rejected.

4.1.6 Performance Evaluation

Finally in this module the performance of the existing and the proposed approaches were illustrated and evaluated. In the existing method the Pessimistic Controllability (PC) Model and (ii) Switched RAT (SR) Model are used to maximize the sum-rate and the service capacity. In the proposed system, the Joint Routing And Dynamic Spectrum Allocation scheme is used. Compared to the existing system we achieve maximum throughput and less delay in the proposed system.

5. CONCLUSION

A framework for distributed resource allocation and admission control in a Cognitive Digital Home (CDH). Two channel access models were considered in the CDH for addressing spectrum coexistence of legacy devices: (i) Pessimistic Controllability (PC) Model where the HG had no influence over legacy devices, and (ii) Switched RAT (SR) Model where the HG had perfect control of legacy devices. Two resource allocation problems (i) Maximizing Sum Rate, and (ii) Maximizing Service Capacity were solved in a distributed manner to reduce the sensing and computation burden. Distributed algorithms were designed using partial dual decomposition techniques. A distributed power control scheme was developed for efficient use of energy. Based on the pricing information obtained from the distributed algorithms, an admission control scheme was designed to improve the system feasibility. For improving the dynamism and scaling a distributed algorithm for joint opportunistic routing and dynamic spectrum access is proposed in multi-hop cognitive radio networks.

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