Research on Cognitive Wireless Networks : Theory, Key Technologies and Testbed

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***Abstract*—Cognitive Wireless Network (CWN), which is a set of heterogeneity networks with the capability of perceiving, planning, deciding and learning according to current multi-domain environment and end-to-end goals, is motivated by the integration, ubiquity and broadband requirements of future networks. But the rising complexity of heterogeneity networks and the need to manage this complexity make the actualization of CWN timely and attractive. Many related projects are built for research teams to do further study. We are undertaking a project called "Basic theory and Key Technologies in Cognitive Wireless Networks" which is one of the major projects in National Basic Research Program (973 Program) approved by the Chinese government. Our research team focuses on issues from network architecture to multi-dimension sensing technologies and radio resource management which are related to each other. In this article, an overview of this project is given by discussing its purpose, research vision, research progress, and testbed.**

I. Introduction

Nowadays, the increasingly rapid development in telecommunication industry is motivated by the meteoric growth in voice and data communication usage. Every year, about 120,000 new base stations are deployed servicing 400 million new mobile subscribers around the world. By 2015 the downlink traffic from cellular handsets is expected to grow more than eight fold rising from 56MB per month to 455MB [1]. Wireless networks are required to provide higher capacity for ubiquitous broadband services such as video conferences, Internet Protocol Television (IPTV), mobile Internet to users. However, existing wireless networks could not satisfy these increasing demands. Firstly, no single Radio Access Network (RAN) can provide ubiquitous service because of the existence of coverage hole. Secondly, the shortage of electromagnetic radio spectrum limits users from experiencing high data rate broadband services. Amazingly, two contradictions are found while looking into these two problems.

Contrary to the vacancy of ubiquitous coverage provides by a single RAN, almost anyplace is covered by at least one RAN. Wireless communication systems are broken into tiny non-communicating islands that users could not handover to the now existing Radio Access Technology (RAT), let alone providing satisfactory and seamless service according to the dynamic change of wireless environment and service requirement. Research in multi-mode terminal mitigates this contradiction to some extent, but the high complexity and low flexibility are the bottlenecks that hinder the development of multi-mode terminals. The autonomy of heterogeneous network management turns to be the key issue, which is becoming more and more important as the system complexity grows higher with the increasing technologies and devices that overwhelm users and operators.

Contrary to the generous consideration that spectrum is a scarce natural resource, measurements show that over 60% of the licensed spectrum below 6 GHz remains unused or under-utilized [2], [3]. To get first-hand data, we took measurements under three typical scenarios for over 1-week period. Our measurement result shows that the spectrum efficiency in many bands is less than 5%. Additionally, results show that wireless networks have distinct characteristics such as spectrum utility, load peak time and coverage. This means that one system is bearing heavy traffic while some others in the overlapped area process much lighter traffic. Then we can infer that spectrum access is a more significant problem than physical scarcity of spectrum of most bands due to legacy command-and-control regulation which limits the ability of potential spectrum users to obtain access to some vacant bands.

Cognitive Radio (CR) provides an alternative solution to many problems including the two contradictions mentioned above. A CR is "a radio that is aware of its surroundings and adapts intelligently" [4] [5]. To deal with the first contradiction, terminals firstly collect information about available RATs by sensing current environment and then automatically access to a proper one according to user behavior and network state when users move to the coverage hole of currently accessed RAT. This is called opportunistic spectrum access in CR. To deal with the second contradiction, vacant spectrum is sensed and allocated to cognitive users dynamically. This is called dynamic spectrum allocation in CR.

CR is not good enough because the goals of CR are limited in improving the performance of a single user. Changes of parameters in protocol layers above the physical layer would impact more nodes; the negotiation process should be done in a more cooperative way considering network-wide optimization goals. Recent research in CR has spirited the concept of the CWN. "A cognitive network is a network with a cognitive process that can perceive current network conditions, and then plan, decide, and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals." [6] We are undertaking a related project named Basic theory and Key Technologies in Cognitive Wireless Networks approved

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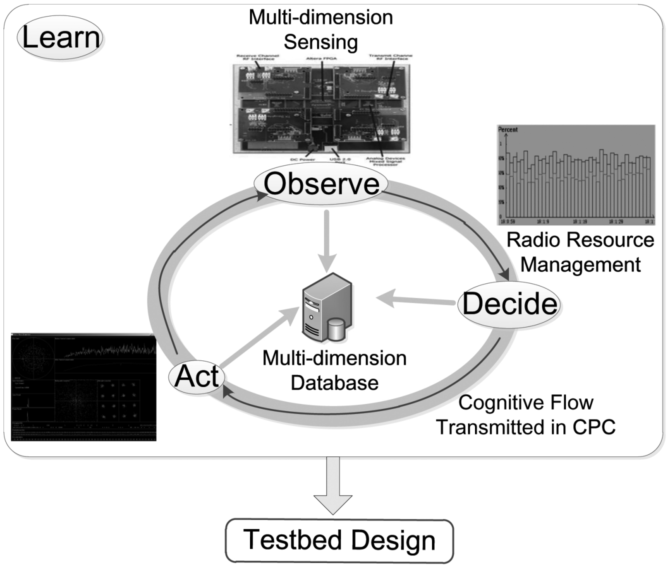

Fig. 1. Cognitive Wireless Network

by the Chinese government. Our research team focuses on issues from network architecture to multi-dimension sensing and radio resource management. Specially, the first CWN testbed in China which works in 2.3-2.4GHz with 20MHz bandwidth is built by our team. The relations between these issues are illustrated in Fig.1.

In this article, an overview of this project is given by introducing its research vision, research progress, and testbed. Three key issues in the project are flexible network architecture, cognitive of multi-dimension environment, and discretionary resource management. They are described in Section II, Section III, and Section IV respectively. The testbed system developed to valid these three key technologies is introduced in Section V. A practical discussion of the implementation of a cognitive wireless network and important areas of future work closes the article in Section VI.

II. Flexible Network Architecture

Static and blocked architecture of traditional network limited the development of wireless networks. Though cognitive radio technology provides a possibility to surmount this obstacle, the control information mingled with cognitive information still cannot meet the need of intelligence. So a flexible network architecture is the fundamental of CWN, based on which the adaptive character of CWN can be emphasized.

A. Overall Network Architecture

Many international standardization organizations defined standards addressing the overall system architecture and information exchange between network and devices, such as IEEE Standards Coordinating Committee 41 (SCC41) and ETSI Reconfigurable Radio Systems (RRS) work group. After looking into these architectures, we designed a new network architecture shown in Fig.2 based on our understanding of end-to-end goal in CWN. This architecture enables devices operate in an opportunistic and dynamic manner under a heterogeneity wireless network environment. Emphasizing on end-to-end goal differentiates this architecture design from others. The corresponding protocol definitions related to the information exchange will be introduced in sections afterward.

The overall network architecture is comprised of three building blocks which are Radio Resource Management and Optimization (RRMO), Reconfigure Controller (RC), and Sensing Information Controller (SIC). SIC block is in charge of collecting information of multi-dimension environment. This multi-dimension information runs through the cognitive circle so that we call it “cognitive flow” which is transmitted in Cognitive Pilot Channel (CPC) and stored in multi-dimension database. The RRMO consists of different modules at terminal side, access network side, and core network side with increasing complexity. This enables the coordination of devices to do distributed decision making which aims at optimizing radio resource usage. Also the RRMO block at the three sides is different in reconfiguration interval which is shortest at terminal side and longest at core network side. Learning and deciding processes are mainly completed in the RRMO block according to the cognitive information which is given by SIC block. Then RC block performs adaptive adjustment following the decision made by schemes with the capability to learn from past decisions and use this experience as a guidance for future behavior. Interface between these blocks are also defined to fulfill the demands of information exchanges.

B. Cognitive Pilot Channel

As one of the candidate solutions for heterogeneous network information delivery for dynamic spectrum sharing in CWN, the CPC techniques are proposed within the E2R project [9] which we participated in. It is an enabler for context perception and cognitive network information delivery through a specific broadcast signaling channel, enabling heterogeneous network information sharing in CWN. CPC is the carrier of cognitive flow which consists of multi-dimension information. There are two categories of CPC schemes which are out-band CPC scheme and in-band scheme. The out-band CPC scheme is brought forward to provide the vital network information to cognitive terminals in the switch-on period by using a common worldwide frequency or a collection of several available frequency bands. And the in-band CPC scheme is proposed to provide more detailed network information in the on-going period by using the specific frequency band of existing RATs.

In terms of the delivery modes of CPC, the broadcast CPC mode delivers the heterogeneous network information of all meshes one by one periodically and continuously in a large coverage area through the downlink channel. Though the broadcast CPC mode has the advantages of large coverage and easy implementation, it faces several problems. Cognitive users could not bear long waiting time when heterogeneous network information is urgently required. However, the broadcast process is time-consuming when the area is divided into

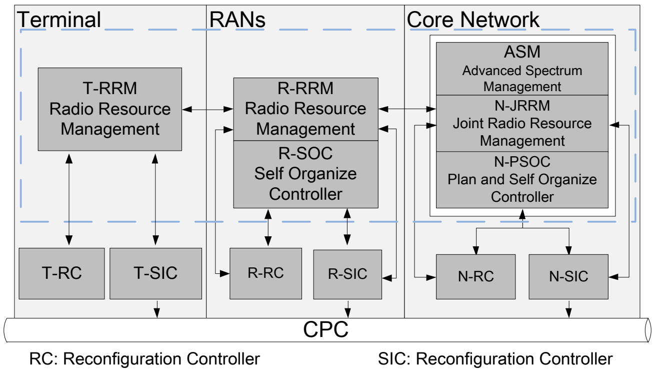

Fig. 2. Architecture of CWN

a great number of meshes. Based on these considerations, the on-demand CPC mode is proposed in [10] with both uplink and downlink channels, through which the cognitive terminals can send requests whenever needed. This on-demand mode needs a CPC Server which is responsible for the network information delivery control. Though the on-demand CPC mode is much more efficient and requires lower bit rate to the broadcast mode, problems still exist when too many requests from a single mesh are received by the CPC Server in a short period. In this scenario, the CPC Server will face the risk of congestion and the duplicate network information delivery of one specific mesh will lead to low efficiency of the whole system under on-demand mode.

III. Cognition of Multi-dimension Environment

A. Collection of Cognition Information

Cognitive process is the preparation of performance optimizations and it aims to obtain the knowledge of operational radio environment and geographical environment, the established policies and its internal states. In addition, the ability to monitor usage patterns, user needs and any subsequent changes. Research on sensing techniques is considered to be the most attractive. Many sensing techniques have been explored [12]. Nevertheless, in order to reliably find more spectral holes for dynamically access, the system needs to monitor and scan wide frequency range. This is usually a time-consuming and power-inefficient procedure. However, the sensing slot is usually too short to build the entire spectrum utilization table that can instruct the dynamic spectrum access procedure. So wideband spectrum sensing is considered as an important technical issue.

Traditionally, the wideband spectrum sensing approach may either divide wideband into several narrow bands to do narrowband spectrum sensing independently or operate over multiple frequency bands at a time. In the former case, the delivery of spectrum occupancy information obtained in different Radio Access Technologies (RATs) becomes a problem [13]. In the latter case, there are still challenges to both hardware design at the RF front-end for a sensing node to scan a lager scope and the development of reliable signal processing algorithms to deal with more samples. Provided that the spectrum is sparse, compressed sensing,(CS) also offers a method to acquire the spectrum information by using a sub-Nyquist sampling rate. A pioneering work is done in [14], where CS is exploited for wideband spectrum sensing. It can alleviate the harsh requirements on the circuitry of the RF front-end.

B. Storage of Cognition Information

Cognition Database is a promising logical entity in Cognitive Wireless Network architecture for storing cognitive information to support the functions implemented in cognitive circle. And by sharing information about the radio environment through cognitive database dissemination, the hidden node problem can be mitigated and the secondary users can coexist with primary users at a price of minimal harmful interference. The cognitive information needs to be well classified and organized in order to leverage and enhance information management, information representation and information access, so that functions of predicting, learning and sharing can be better supported.

There are different RATs in CWN that the information related to RATs is comprehensive, including information of space, time, frequency, user, network and different layers of system. The cognitive database should be divided into several domains in terms of its nature, and the cognitive information in it should be managed based on the dimension division, such as wireless dimension, network dimension, user dimension and policy dimension. This multi-dimension cognitive database is disposed in a hierarchical manner as shown in Fig.3.

The connotation that those domains hold are illustrated as follows:

- The wireless dimension:
  This wireless dimension is composed of the parameters of radio transmission characteristics considering different RATs, such as transmit power, spectrum band, Signal to Interference plus Noise Ratio (SINR), transmission rate, radio resources bandwidth, and etc.
- The network dimension:
  Network dimension consists of the information reflecting the network status, such as traffic, system load, network revenue, network delay, routing, scheduling scheme, node topology, and etc.
- The user dimension:
  This dimension focuses on information concerned by users, such as location information, Quality of Service (QoS) request, user Identities (IDs), accounting, and etc.
- The policy dimension:
  Policy is the guideline that manages radio resources, such as communication rules and spectrum policy.

IV. Discretionary Resource Management

The resource management are required to be performed in a cooperative way considering network-wide optimization goals. However, communication of network state information is concealed by the layered protocol architecture, making individual elements unaware of the network status perceived by other

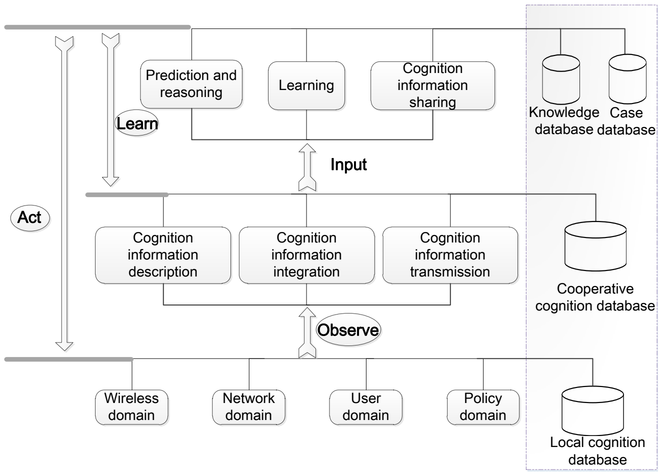

Fig. 3. Multi-dimension cognitive database

elements. As a result, any response that an element made to the network stimuli can only be made in the context of its limited scope. In link parameter adaption aspect, several efforts using cross-layer methods [16] have been made. [17] designs a cross-layer optimization frame-work in which the source coding, allowable retransmission, and adaptive modulation and coding have been jointly optimized for video transmission quality. In [18] the Channel State Information (CSI) in PHY layer is used to minimize the transmit power then to maximize the throughput for single user. [19] develops a cross-layer design which combines adaptive modulation and coding at the physical layer with a truncated automatic repeat request protocol at the data link layer to maximize spectral efficiency under prescribed delay and error performance constraints. In order to guarantee the end-to-end network performance, cross-layer design is not enough. Multi-objective optimization with learning ability which jointly considers all goals in the optimization process is supposed to get better performance. For example, [20] transforms the dynamic network self-optimization problem into a multi-agent reinforcement learning problem by applying enhanced Q-learning.

Spectrum resource management is a key aspect of radio resource management to fully utilize this scarce resource. Recently, lots of research has been directed to the topics on DSA, which falls into two categories: spectrum underlay and spectrum overlay. The first one permits the coexistence of primary and secondary users but impose severe constraints on the transmission power of secondary users, so that they operate below the noise floor of primary users. The second one is also called Opportunistic Spectrum Access (OSA) [15] , which does not necessarily impose severe restrictions on the transmission power of secondary users, but rather on when and where they can transmit. In this case, the secondary system is transparent to the primary system, which means secondary users have to promptly release the frequency bands upon primary user's access request. There is more research focus on the second category.

V. TESTBED

The industrialization of CWN requires development in step by step with a long period. So a testbed is needed to provide verification for theory output from tasks mentioned above. We designed a testbed with 20MHz bandwidth which works in 2.3-2.4GHz refers to SISO TD-LTE system. To add functions related to cognition the protocol has been modified based on that of 3GPP 36 series R8 accordingly.

A. Testbed design

We were facing the problem of choosing a proper frequency band as the working spectrum channel of the testbed. Firstly, there should be primary users working in the chosen frequency so that the cognitive function can be verified. Secondly, the frequency primary users work in will be planned in future and there would be more interference in it so that the experiments can be of realistic significance. Finally, the frequency for experiment should not be completely allocated so that cognitive users may have more available spectrum to access without much interference on existing system. We used 2.3-2.4GHz as the working spectrum band since it is allocated to TD-LTE (TD-SCDMA Long Term Evolution) to operate the experiment at present. It is shown that there is little signal in 2.3-2.4GHz so that the experiment will not cause more interference for existing system. There is some signal detected so that cognitive function can be verified. It is analyzed that the signal detected is from radar system 2400-2483.5MHz for ISM (Industrial, Scientific and Medical), so it may cause adjacent-frequency interference to 2.3-2.4GHz. A photo of this verification testbed is shown in Fig.4. The protocol is designed based on modification and simplification of 3GPP 36 series R8. We add functions related to cognition and decrease the complexity of realizing.

B. Deployment Scenarios

1) Dynamic Spectrum Allocation: Advanced spectrum management is proposed to actualize the basic idea of DSA which is to increase spectrum efficiency by opening the licensed spectrum to cognitive users. Advanced spectrum management performs spectrum allocation in long-term and short-term manner corresponding to coarse and finer-grained scheduling.

The spectrum allocation in both manners are performed according to the sensing result. The long-term allocation schemes assign spectrum bands to each cognitive base station (CBS) on the order of hour. The short-term allocation assigns spectrum bands to each CBS dynamically on the order of minute, because service arrival rate and service length of both primary users and cognitive users vary with time significantly. Compared with the long-term allocation schemes, short-term ones make more flexible and quick decisions. So advanced allocation schemes with learning ability are still to be studied. Our test based on a simple short-term allocation scheme shows that the spectrum efficiency increased by 20-30%.

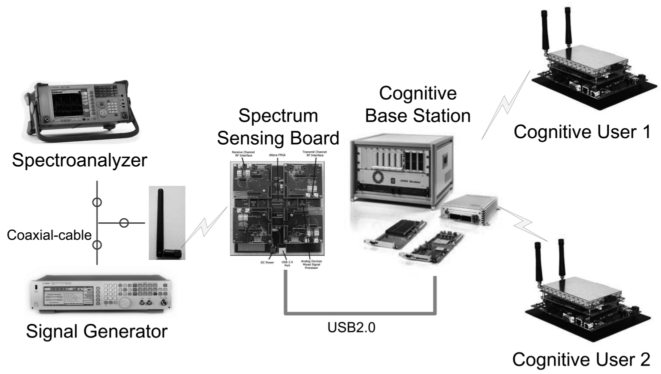

Fig. 4. Verification Testbed

2) Joint Radio Resource Management: The autonomy of Joint Radio resource Management (JRRM) between heterogeneous RATs is studied. Through the "trial-and-error" interaction with the multi-dimension environment, the JRRM controller learns to give the best allocation for each service in terms of both the access RAT and the service bandwidth. The target is to improve the spectrum utility considering different service ability of each RAT while reducing the blocking probability as much as possible.

Load balance is an important issue to be addressed in JRRM. Generally, system overload can be avoided by network planning, admission control, and packet scheduling. But actually overload or load unbalance is unavoidable due to the untimely network monitoring and burst of traffic. Under heterogeneous environment, not only inner-RAT but also inter-RAT load balance control is needed to overcome the conflict between arrival rate and service rate. While one RAT is predicted to be overloaded, some services are passed on to another RAT which is detected carrying light traffic. This process is required to be seamless without interrupting current communication or introducing interference to users in the target RAT. This can be seen as a special case for spectrum handover.

VI. Summary and Future Work

To integrate the heterogeneous networks and improve the spectrum efficiency, a project on CWN is underway in China. Flexible network architecture, cognition of multi-dimension environment, and discretionary resource management are discussed in this article as three key technologies which are required to be further studied to make CWN a reality. Also a testbed is developed aiming at verifying the effectiveness of these technologies in solving the two problems mentioned above.

However, there is still plenty of work to do, such as development of performance metrics for systemically defining CWN in order to provide a foundation for analyzing and comparing networks performance in terms of spectrum efficiency and user experience. Also, a series of advantages of CWN is proposed without measuring the cost. CWN is much more complex than current networks that the energy cost of its component is naturally higher. So the issue of green communications within the large framework of CWN needs to be considered.

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