PCDS: Power Control with Opportunistic Scheduling for Cognitive Radio Networks

Hang Qin¹,² Student Member, IEEE
¹Computer School, Yangtze University, Jingzhou, 434023, China
²State Key Laboratory of Software Engineering, Wuhan University, Wuhan 430072, China
hangqin100@hotmail.com

Jun Su³, Youfu Du⁴
³Computer School, Yangtze University, Jingzhou, 434023, China
³sijosix@hotmail.com
⁴dyf@yangtzeu.edu.cn

Abstract—Cognitive Radio network (CRN) is a network composed of elements that, through learning and reasoning, dynamically adapt to varying network conditions in order to improve spectrum efficiency for wireless networking. To investigate opportunistic scheduling, this paper develops a methodology based on the jointly consideration of the power control, spectrum allocation and flow routing. The two-phrase cross-layer design with multi-user interference consideration is explained. The influences from the diverse transmission power control are identified. To support user communication sessions, the Power Control with Decentralized Scheduling (PCDS) algorithm with reconfiguration management scheme is presented, which can dramatically improve spectral efficiency and performance of a multi-hop network. Using Bandwidth Foot Product (BFP) as a link metric, the power control granularity is predicted by a proposed strategy that considers radio resource management. The experimental results show that PCDS with reconfiguration can achieve good power granularity control and high spectrum allocation success rate.

Index Terms—cognitive radio; power control; opportunistic scheduling; cross-layer design; end-to-end reconfiguration.

I. INTRODUCTION

Cognitive radio (CR) has recently been proposed by Federal Communications Commission (FCC) as a possible solution to the spectrum scarcity problem that plagues current wireless networks [1-2]. Cognitive radio, which is viewed as an enabling technology for dynamic spectrum access, can learn from its surroundings and adapts its functionalities to best serve the user [3-4]. The advances of CR technologies make more efficient and intensive spectrum access possible. The FCC began to consider more flexible and comprehensive use of available spectrum. The NeXt Generation (xG) program of the DARPA also aims to exploit the existing wireless spectrum opportunistically based on CR technologies [5].

As the demand for wireless services increases, efficient use of resources grows in importance. A fundamental component of radio resource management is transmitter power control. It is well known that minimizing interference using power control increases capacity and also extends battery life [6]. The problem of power control comes up because in a CR network, the transmissions of the different nodes interfere with each other unless having been assigned orthogonal resources. In addition, power control is of paramount importance to limit multi-user interference and, hence, maximize the spatial reuse of resources.

Power control clearly influences the network topology, which is a concern of the network layer [7]. It also impacts how far apart can two ongoing communication sessions be without interfering with each other, which is a concern of the MAC layer. Power control is also linked to the processing at the physical layer, because the signal processing at the physical layer determines how stringent the requirements on the power control need to be. All these factors determine the end-to-end throughput. Furthermore, the transmitted powers determines the lifetime of the nodes which one would want to maximize. Hence, the problem of power control cannot possibly be handled at any one layer in isolation, as is done while designing protocols in the framework of the layered architectures. It is thus a problem that, by its very nature, requires cross-layer design. It is no surprise then that a number of cross-layer design proposals in the literature have looked at power control in a cross-layer design framework [8-9].

II. RELATED WORK

An excellent survey of recent research on power control of CR can be found in [10]. This paper develops a formal mathematical model for scheduling feasibility under the influence of power control. Two texts, [11] and
[12], provide a more complete technical background to multi-hop cognitive radio devices.

Other research investigates power scaling to cognitive radio networks. Hoven et. al. examines the effects of heterogeneous propagation path loss functions and justify the feasibility of multiple secondary users with dynamic transmit powers in [13]. Xie et. al. explore a model of wireless networks that particularly takes into account the distances between nodes, and study a performance measure that weights information by the distance over which it is transported in [14]. The research presented here is in many ways an extension to [10] and [14].

With the increasing demand for wireless data services, it is necessary to establish power control algorithms for information sources other than voice. In [15], Saraydar presents a power control solution for wireless data in the analytical setting of a game theoretic framework, in terms of a pricing function of the transmit power. Game theory is also applied to power control in CDMA wireless networks in [16]. In [17], the problem of finding an optimal link scheduling and power control policy is addressed to minimize the total average transmission power in the wireless multi-hop network. Finally, the cross-layer design framework to the multiple accesses in contention-based wireless ad hoc networks is studied in [17].

CR enables a network to reconfigure its operation according to application requirements, environmental conditions, and operational policies. Thus exploiting end-to-end reconfiguration has attracted enormous interests in recent years. In [18], the authors showed how parameters at the physical, data link, network, and application layers interact to affect performance. In [19], the authors described a framework on architectural tradeoffs and protocol designs for CRN at both the local network and the global inter-network levels. This architectural study will lead to the design of control management and data interfaces between CRN. Furthermore, our technique requires a broad set of configuration management input factors, including decision making and policy enforcement.

III. PRELIMINARIES

To satisfy the coordination capabilities, several inter-module interfaces and protocols can be implemented, specifically:
- **Control Plane** acts as a cross-layer network management overlay, which can interface with the network layer, and can has representations of the cognitive sub-network state to IP core network.
- **Flexible MAC** which addresses programmable functionality with dynamic selection of channel sharing, in terms of observed network conditions and traffic demands.
- **Network Layer** that support service discovery, naming, addressing and routing in ad hoc wireless environment.
- **Reconfiguration** that can be utilized to set up network connectivity after a reconfigurable CR terminal is turned on or enters a new service area.

According to the CR architectural elements in Fig. 1, various functionalities are required to support spectrum coordination in CRN. The CRN can be deployed in network-centric, distributed, ad hoc, and mesh architectures, and serve the needs of both licensed and unlicensed applications. The basic components of CRN are Cellular System (GSM/GPRS, cdma2000), MAN System (WiMax), and Short Reach System (WLAN802.11/b/g/n). These basic components make up for three kinds of network architectures in the CRN.

Consequently, terminals are divided into Fixed CR Terminals and Reconfigurable CR Terminals. The **Cognitive Plane** will utilize both overlay-based mechanisms for communication within a subnet, as well as support the concept of reconfigurable CR terminals which will serve as a gateway between local network layers. Inspiring the idea of multiple network layers tailored to specific applications or communication flow...
types, planes provide a variety of optimization points, and may be tailored to the application.

IV. SPECTRUM ALLOCATION WITH DECENTRALIZED SCHEDULING

Fig. 2 shows the CRN scenario consisting of $N$ primary services operating on the different frequency spectrum $F_i$ and a secondary service which serves a group of secondary users willing to share spectrum with the primary services. In terms of time slots in a wireless access system, primary service $i$ could provide portions of the available spectrum $F_i$ with decision maker to the secondary service. The spectrum can be shared among multiple secondary users where the base station or access point governs the radio transmission on the allocated spectrum. The secondary users utilize adaptive modulation for transmissions on the allocated spectrum in a time slotted manner. The spectrum demand of the secondary users relies on the transmission rate for the adaptive modulation in the allocated frequency spectrum.

Each node has two spectrum management decisions: a Diverse Transmission Power Control with local Decentralized Scheduling and a Decision Maker with the acceptance and distribution of frequency bands between participating CR nodes. In Fig. 2, frequency bands are submitted by a local user community to the node’s decentralized scheduling and flow routing. With the Decision Maker, it is queued and either started locally or moved to other nodes. The on-site assignment to primary services is finally done by the local diverse transmission power control. Firstly, the decision maker (1) accepts spectrum from a local user community, and then either (2) allocates frequency bands to the local node’s decentralized scheduling and flow routing or (3) offers them to the decision maker of other nodes.

As the frequency band is arriving over time, decentralized scheduling and flow routing poses two challenges: One is to find a decision strategy that accepts submitted frequency bands and determines whether to hand over a frequency band to the local spectrum scheduling or to a remote node while keeping the performance of the spectrum utilization high, the other is to assign ultimately accepted frequency bands that are waiting in the queue to local resources in an efficient way.

V. DESIGN OF DISTRIBUTED OPTIMIZATION ALGORITHM

A. Joint Scheduling-Power Strategy

In a wireless network, each node is associated with an interference range, which occurs with two pairs of nodes which use transmissions that overlap in time and frequency. The nodes observe the interference as a low Signal to Interference and Noise Ratio (SINR), and it should increase transmission power to achieve an SINR increasing. As the power of one link’s transmitter is increased, the other link will suffer a lower SINR and hence increase its power. Each radio should maximize SINR at intended receiver by increasing its own transmission power. Accordingly, both links will have low SINR and poor performance, or the link with the more powerful transmitter could completely cover with the other. Clearly, it is a poor solution, due to now each radio which is transmitting much more power than is required, reducing battery life, raising power consumption, and increasing potential interference to other users.

In this section, the two-phrase Power Control with Decentralized Scheduling (PCDS) algorithm is proposed. This algorithm is executed at the beginning of each time slot to meet excessive interference levels developed in some slots. The PCDS algorithm determines the set of users that can safely transmit in the current slot without interrupting other transmission. Consequently, the purpose is as follows: One is to identify the set of users who can attempt transmission in a given time slot, the other is to determine the set of powers needed to satisfy SINR constraints at their respective receivers.

Case 1: In CRN, a transmission is active if and only if it satisfies the following three conditions: (i) A node can
transmit and receive simultaneously. (ii) A node cannot receive from more than one neighbor at the same time. (iii) A node receiving from a neighbor could be spatially separated from any other transmitter by at least a distance $R_T(p)$. Nevertheless, if nodes use unique signature sequences, then the condition (ii) and (iii) can be taken out, and the condition (i) only depicts an active transmission case. The objective of the condition (iii) is to carry out spatial separation among simultaneous transmissions to decrease interference with unintended receivers. With decentralized scheduling, the choosing of $R_T(p)$ affects the amount of eliminated interference. On one hand, if $R_T(p)$ is too large, a number of interferences are eliminated in the decentralized scheduling phase. On the other hand, if $R_T(p)$ is small, no spatial separation between simultaneous transmissions is provided, and most of the interference could be passed to diverse transmission power control phase. As a result, the choice of $R_T(p)$ generally depends on the minimum acceptable SINR levels.

Case 2: Let $p_{ij}^m$ be the transmission power with link $i \rightarrow j$ on band $m$, a transmission is passive if and only if there is a set of transmission powers, $p_{ij}^m \geq 0$, which accounts for the following problem:

$$\min_{p_{ij}^m} \sum_{m \in \text{all links}} p_{ij}^m$$

\text{s.t.} \quad \text{SINR}_{ij} \geq \beta, p_{ij}^m \in \{0,1,2,\ldots,Q\}, \quad \text{where} \quad Q \quad \text{is the number of transmission power levels at a transmitter.}

The PCDS algorithm with joint scheduling-power strategy is as follows: Firstly, examining the active conditions of a given transmission case is much easier and computationally more efficient than examining the passive conditions, which involves solving the optimization problem. Secondly, given diverse transmission power control, eliminating strong levels of interference in the decentralized scheduling phase is essential.

The decentralized scheduling phase could examine whether the case in the current slot is correct or not. If correct, it proceeds to diverse transmission power control phase. Otherwise, it searches for a correct subset of users by deferring the transmissions of some of the users causing high interference to the next slot. Diverse transmission power control phase could investigate Case 2 specified in the decentralized scheduling phase. If it turns out to be in Case 2, the specified nodes start transmission in the current slot using the determined set of transmission powers. Otherwise, it is transferred again to the decentralized scheduling phase where search is needed to find the optimum subset of users who are passive.

Notice that the objective is to have the maximum number of transmissions that can be successfully detected at their receivers in time slot, this maximizes the spatial reuse of spectrum resources. As a result, the decentralized scheduling could solve two problems, namely active scenario and passive scenario. The objective in the first problem is to determine the transmission scenario that solves the following constrained optimization problem \[ \max |S|, S \text{ is an active scenario, where } S \text{ is cardinality of the transmission scenario } S, \text{ i.e. number of links in scenario } S. \] On the other hand, the objective in the second problem is to determine the transmission scenario $Z$ that solves the optimization \[ \max |Z|, \text{ where } Z \text{ is an passive scenario.} \]

Since the size of the search space grows in an exponential manner with the number of links in the transmission, the complexity of the previous two problems is attributed to their combinatorial nature. This makes a major hindrance toward finding the optimum schedule and renders heuristic solutions unavoidable. For the active scenario search problem, a simple strategy is to examine the set of active scenario constraints sequentially and defer users’ transmissions to resolve the conflicts. It is clear that this algorithm is suboptimal in the sense that it could lead to deferring more transmissions than needed to reach an active scenario. On the other hand, for the passive scenario search problem, a heuristic policy is examined. It suggests deferring the user with minimum SINR as an attempt to lower the level of multiple access interference. This might allow other users to converge to the optimum power vector quite fast. Note that the latter strategy lends itself to distributed implementation if the SINR measurement at each receiver is fed back to all transmitters with efficient information dissemination.

B. Global solution with diverse transmission power

The process of frequency bands exchange can be realized on the basis of two different scenarios: the active delegation asks the local decision maker to offer frequency bands to remote nodes in an active way, and the passive delegation asks remote nodes to request frequency bands that the local decision maker could dispatch. In each scenario, the local decision maker has to publish information on the contents of its local waiting queue. Depending on the policy of administrative domain, this data can be restricted to a subset. The decision on how many and which frequency band to disclose to remote nodes is in any case left to the local decision maker. In PCDS, let $f(l)$ be achieved data rate for session $l$, $f(l)$ be data rate attributed to session $l$ on link $i \rightarrow j$, $c_{ij}$ be remaining capacity on link $i \rightarrow j$. The PCDS is done via two alternating phrases, namely decentralized scheduling phrase and power control phrase.

Decentralized Scheduling Phrase:

1. Given a transmission case in slot
2. if this scenario is active
3. run the power control algorithm for this active scenario
4. if the scenario is passive
5. nodes use the obtained set of powers to send their packet;
6. goto the next slot
7. else search for the optimum passive subset of users
8. else search for the optimum active subset of users
The global solution with diverse transmission power creates a connected network but does not set all transmission ranges to the same value. Instead, it tries to find a minimum power level for every node individually.

The power control phrase minimizes the overall transmission power consumption for the entire network, but it may result in asymmetric communication links, e.g., one node can receive data from a far neighbor which uses a higher transmission power, but can not answer directly due to its smaller transmission power. Even if it is possible to construct networks where this algorithm does not find minimum power levels for all nodes, diverse transmission power vastly outperforms any other method. It would be necessary to restrict the search for not connected neighbors to nodes in other connected components. Thus, diverse transmission power is used as a comparison case, this algorithm also uses global knowledge, and equivalent local implementations are not obvious.

**Power Control Phrase:**

1. Let source node’s achieved data rate be $\infty$;
2. for the first hop to the last hop
3. for each band $m$ in **Decentralized Scheduling**, let node $i$’s the maximum allowed transmission power be $0$;
4. if remaining capacity on link $i \rightarrow j > 0$
5. Node $i$ sets $f(l) = \min\{c_{ij}, f(l)\}$;
6. if there is a band $m$ with active delegation in
7. Decentralized Scheduling
8. Revoke all scheduling decisions done in this iteration, scheduling is feasible;
9. if there is at least one band with link $i \rightarrow j$ with passive delegation on frequency band $m$
10. if the increased capacity under the maximum allowed transmission power is smaller than $f(l)$
11. node $i$ computes the increased capacity and updates the flow rate by this capacity;
12. if band $m$ can be used on link $i \rightarrow j$
13. Let link cost of node $i$ be $\infty$;
14. Revoke all power control/scheduling decisions done in this iteration, scheduling is infeasible

### Decentralized Scheduling

1. Revoke all scheduling decisions done in this iteration, scheduling is feasible;
2. if there is at least one band with link $i \rightarrow j$ with passive delegation on frequency band $m$
3. if the increased capacity under the maximum allowed transmission power is smaller than $f(l)$
4. node $i$ computes the increased capacity and updates the flow rate by this capacity;
5. node $i$ tries each band in the non-decreasing order of the maximum allowed transmission power
6. if band $m$ can be used on link $i \rightarrow j$
7. Let link cost of node $i$ be $\infty$;
8. Revoke all power control/scheduling decisions done in this iteration, scheduling is infeasible

### C. End-to-end Reconfiguration

In terms of the bandwidth utilization, a reconfigurable CR terminal requests additional frequency bands or releases unused bandwidth. This bandwidth adjustment is done within an aggregation link, allowing flows in the same traffic class to share spectrum bandwidth. The end-to-end reconfiguration [20] process is as follow:

When a new flow arrives at a reconfigurable CR terminal, the reconfigurable CR terminal assigns a VIP (Virtual IP Path) to the incoming flow from VIP table and finds if the bandwidth utilization on the assigned VIP exceeds the predetermined upper threshold. If the bandwidth utilization exceeds the predetermined upper threshold, the reconfigurable CR terminal could increase the bandwidth of the frequency bands.

As it can be seen in Fig. 3, the function description of reconfiguration protocol consists of download, configuration and realization procedure. With the
The simulation results are presented to demonstrate the performance of PCDS algorithm. The purpose is to validate the efficacy of the solution and to offer additional insights on decentralized scheduling with power control.

Each unit for bandwidth, rate, distance, and power with appropriate dimensions is normalized. Given a 20 node ad hoc network every node randomly located in a 50×50m area, there are |M|=10 frequency bands in CR network and each band has a bandwidth of W=50Mbps. Each node may only use one of the frequency bands. In the simulation, this is done by randomly selecting a subset of bands for each node from the pool of 10 bands. It is assumed that there are |L|=6 user communication sessions, with source node and destination node randomly selected and the rate of each session is randomly generated from 10Mbps to 100Mbps.

In this section, the objective bandwidth-footprint-product (BFP) [10] is considered, which better depicts the spectrum and space occupancy for a CR network. Let \( R(p) \) and \( p^{\text{min}} \) be the interference range under transmission power \( p \) and full transmission power \( P \). Let \( W \) be the bandwidth of a frequency band. Let \( p^* \) be the transmission power from node \( i \) to node \( j \) on band \( m \). Let \( N \) be the set of nodes in the network. Let \( M_i \) be the set of available bands at node \( i \) \( \in N \). Let \( T^m \) be the set of nodes that node \( i \) can transmit to on band \( m \). The so-called footprint refers the interference area of a node under a given transmission power, i.e. \( \pi \cdot (R(p))^2 \). Since each node in the network will use a number of bands for transmission and each band will have a certain footprint corresponding to its transmission power, an important objective is to minimize network-wide BFP, which is the sum of BFPs among all the nodes in the network. Consequently, the objective is to minimize \( \sum_{i \in N} \sum_{m \in T^m} W \cdot \pi(R(p^*))^2 \), which is equal to \( \pi(R_{\text{max}}^*)^2 \sum_{i \in N} \sum_{m \in T^m} (p^* / P)^{\alpha} \cdot W \). Since \( \pi(R_{\text{max}}^*)^2 \) is a constant factor, it can remove it from the objective function.

### A. Power Control Granularity with BFP

The solution procedure is implemented with a 15 node network described above for different level of power control granularity (Q). It is clear that Q=1 corresponds to the case that there is no power control, i.e., a node uses its peak power \( P \) for transmission. When \( Q \) is sufficiently large, the discrete nature of power control diminishes and power control becomes continuous from 0 to \( P \).

Fig. 4 illustrates the results from different decentralized scheduling with PCDS algorithm. Note that power control phrase has a significant impact on BFP, and the scenario with decentralized scheduling has an advantage over the scenario without it. Comparing the case of no power control and the case of \( Q=20 \), it is clear that there is nearly a 60% decrease in the total BFP, while the BFP is a non-increasing function of \( Q \). But as \( Q \) becomes very large, e.g. 13 in this network setting, further increase in \( Q \) will not have much decrease on BFP. For practical purpose, it is concluded that the number of required granularity levels to obtain a reasonably good result does not need to be a very large number.

![BFP as a function levels of power control](image)

**Figure 4.** BFP as a function levels of power control

### B. Power Level with Iteration

With the increasing of \( N, |N|=15, 20, 30 \) and 40 nodes are randomly placed in 50×50m area. Fig. 5 and Fig. 6 show the comparison of PCDS power control with the traditional method [21]. It is clear that the total transmission power of PCDS reaches saturation value after the second iteration, and reaches the maximum after
the third iteration, with the total power less than the traditional ways. In Fig. 5, the new program requires only about the 62.2% of total power for traditional power control algorithm with 20 users, while it requires only about the 84.3% with 15 users. In Fig. 6, the new program requires only about the 43.5% of total power for traditional power control algorithm with 40 users, while it requires only about the 55.7% with 30 users. With the increase of users, the transmission power of traditional method of power control not only significantly increased, but also more difficult to control and tend to occur instability.

The reconfiguration mechanism is implemented in C++, where the control radio uses 802.11b operating at fixed channel 1 with 2Mbps rate covering about 250m. The control MAC uses the IEEE 802.11 standard. For generality, the data radio can be accomplished with generic radios, and 802.11a OFDM radio parameters at 5GHz is used for Cognitive Plane with 8 channels of 20MHz. The scenario consists of varying numbers of CR nodes in a 1km × 1km of unit area, where nodes are randomly placed in the network and boot up at random times. Based on network setup time, control overhead used and estimated achievable end-to-end rate, the spectrum coordination is discussed. By completing the reconfiguration process, the maximum network setup time is the time from the start of the first node to the time all nodes in the network achieve global awareness. To evaluate the protocol, different traffic source and destination pairs are chosen randomly to perform data ON/OFF sessions.

Fig. 7 shows the simulation results for the protocol and protocol task scheduling. With increasing numbers of source and destination pairs in the network, the average frequency allocation success ratio decreases. It is clear that as increasing node density, this ratio improves mainly because the protocol task scheduling allocates minimum required power to achieve the maximum supported bit-rate, then it potentially increases the space reuse of the limited data channels. The reconfiguration succeeds if every hop is configured with a matching frequency from hop sender to receiver.

C. Reconfiguration Validation

The reconfiguration mechanism is implemented in C++, where the control radio uses 802.11b operating at fixed channel 1 with 2Mbps rate covering about 250m. The control MAC uses the IEEE 802.11 standard. For generality, the data radio can be accomplished with generic radios, and 802.11a OFDM radio parameters at 5GHz is used for Cognitive Plane with 8 channels of 20MHz. The scenario consists of varying numbers of CR nodes in a 1km × 1km of unit area, where nodes are randomly placed in the network and boot up at random times. Based on network setup time, control overhead used and estimated achievable end-to-end rate, the spectrum coordination is discussed. By completing the reconfiguration process, the maximum network setup time is the time from the start of the first node to the time all nodes in the network achieve global awareness. To evaluate the protocol, different traffic source and destination pairs are chosen randomly to perform data ON/OFF sessions.

Fig. 7 shows the simulation results for the protocol and protocol task scheduling. With increasing numbers of source and destination pairs in the network, the average frequency allocation success ratio decreases. It is clear that as increasing node density, this ratio improves mainly because the protocol task scheduling allocates minimum required power to achieve the maximum supported bit-rate, then it potentially increases the space reuse of the limited data channels. The reconfiguration succeeds if every hop is configured with a matching frequency from hop sender to receiver.

In summary, this paper addresses the issue of cross-layer design of power control and flow routing with interference constraints in CRN. The radio resource management with spectrum coordination protocol for reconfiguration is identified and explained. Power Control with Decentralized Scheduling (PCDS) algorithm, which is valid up to the multi-user interference and includes transmission power adjustment, is developed and verified for maximizing the spatial reuse of resources. Based on this algorithm, analyses indicate that joint scheduling-power strategy is capable of solving the multiple accesses for an admissible set of users along with decentralized scheduling. It is revealed that this opportunistic algorithm is responsible for coordinating independent users’ transmissions to reduce levels of interference inherent to CRN.

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers for their constructive suggestions to improve the quality and presentation of this paper. This paper is significantly extended from the conference version submitted to the IEEE CNMT 2009. This research was
supported by an International S&T Cooperation Program of China under contract number 2007DFA11000.

REFERENCES


Hang Qin received the B.S. degree from Central China Normal University, Wuhan, China, in 2001, and the M.S. degree from Huazhong University of Science and Technology, Wuhan, China, in 2004, all in computer science. He is currently pursuing the Ph.D. degree at the Software Engineering State Key Laboratory, Wuhan University, Wuhan, China.

Jun Su received the B.S. degree from national technical university of Ukraine, Ukraine, in 2001, and the M.S. degree from national technical university of Ukraine, Ukraine, in 2004, all in Computer System and network. He is currently pursuing the Ph.D. degree at Terminopil National Economic University, Ukraine. Now, he is a lecturer in Yangtze University. He has published over 10 papers. His research interests include network management, information security, software engineering, and wireless communication.

Youfu Du received the B.S. degree from Nankai University, Tianjin, China, in 1982, and the M.S. degree from Naval University of Engineering, Wuhan, China, in 1988, all in computer science. Now, he is a professor of computer science and engineering and the dean of the School of Computer Science and Technology, Yangtze University. He has published over 30 papers. His research interests include network security, artificial intelligence, database application, and wireless communication.