Interference Modeling and Analysis in Cognitive Radio Networks

Yanxiao Zhao, South Dakota School of Mines and Technology USA
Bighnaraj Panigrahi, South Dakota School of Mines and Technology USA
Kazem Sohraby, South Dakota School of Mines and Technology USA
Wei Wang, South Dakota State University, USA

Abstract: Cognitive radio networks (CRNs) have received considerable attention and viewed as a promising paradigm for future wireless networking. Its major difference from the traditional wireless networks is that secondary users are allowed to access the channel if they pose no harmful interference to primary users. This distinct feature of CRNs has raised an essential and challenging question, i.e., how to accurately estimate interference to the primary users from the secondary users? In addition, spectrum sensing plays a critical role in CRNs. Secondary users have to sense the channel before they transmit. A two-state sensing model is commonly used, which classifies a channel into either busy or idle state. Secondary users can only utilize a channel when it is detected to be in idle state. In this paper, we tackle the estimation of interference at the primary receiver due to concurrently active secondary. With the spectrum sensing, secondary users are refrained from transmitting once an active user falls into their sensing range. As a result, the maximum number of simultaneously interfering secondary users is bounded, typically ranging from 1 to 4. This significant conclusion considerably simplifies interference modeling in CRNs. We present all the cases with possible simultaneously interfering secondary users. Moreover, we derive the probability for each case. Extensive simulations are conducted and results validate the effectiveness and accuracy of the proposed approach.

Keywords: Interference model; primary user; secondary user; cognitive radio networks

1. Introduction

The recent decade has witnessed rapid proliferation of wireless technologies and their significant impact on all aspects of our lives. However, these disruptive wireless technologies exhaust the limited radio spectrum, which is referred to as spectrum scarcity (Wang et al., 2011; Peha, 2009). This issue leaves little or no spectrum for future demands. Spectrum scarcity has become increasingly serious leading to intensified attention. Cognitive radio network (CRN) is commonly envisioned as a promising solution to relieve spectrum scarcity and significantly improve spectrum efficiency. In recent years, CRNs have been gaining considerable attention and related research on a variety of topics can be found in the literature (Gao et al., 2004; Qiu et al., 2012; Liu et al. 2008; Zhao et al., 2011; Lee et al, 2012).

A typical CRN is comprised of two types of users: primary users (PUs) and secondary users (SUs). PUs are authorized to utilize licensed bands/channels whenever they have demands. In contrast, SUs are not licensed users, but they are allowed to temporarily access channels without harmful interference to the PUs. If the interference from SUs to PUs is dominant and destructive, SUs have to take necessary actions to avoid it. For instance, SUs
may need to withdraw from the channel immediately or reduce their transmission power. This distinct feature of CRNs raises an essential and challenging question, i.e., how to accurately estimate or predict interference from SUs to PUs. This topic has recently attracted considerable attention (e.g., Hong et al, 2008; Chen et al, 2010; Rabbachin et al, 2011). Most of the existing models and related analysis are significantly complex.

In this paper, our goal is to estimate the total interference from SUs at any PU receiver by developing a considerably simpler probabilistic interference model in which spectrum sensing is taken into account. Spectrum sensing plays a critical and fundamental role in CRNs. SUs have to continually monitor the channel before their transmission. The two-state sensing model is commonly used in the process of spectrum sensing, which classifies a channel into either busy or idle state (Zhao et al, 2012). Secondary users can only be allowed to utilize a channel when it is detected as idle.

With the two-state sensing model, the SUs that detect an active user, either a PU or another SU in their sensing ranges are prohibited from transmitting. As a result, it is interesting to observe that the maximum number of simultaneously interfering SUs is finite, typically ranging from 1 to 4 (Zhao et al, 2013). We are inspired by this significant conclusion and propose a simple probabilistic interference model for CRNs. All cases with simultaneously interfering SUs to a PU receiver are analyzed. Furthermore, in each case, the interference to primary users is derived and the corresponding probability is thoroughly investigated as well. This promising and effective approach is expected to shed light on interference modeling in CRNs with spectrum sensing.

The rest of the paper is organized as follows. In Section 2, we briefly introduce related work. Section 3 presents the network model along with assumptions. In Section 4, we introduce the proposed interference modeling along with in-depth mathematical analysis. The simulation results and discussions are presented in Section 5. Concluding remarks are stated in Section 6.

2. Related Work

Spectrum sensing is a fundamental and essential process in CRNs, which can generally be classified into two groups: local sensing and cooperative sensing (Akyildiz et al, 2011). In local spectrum sensing, each SU makes a decision independently about the channel state from its own information. The local spectrum sensing techniques include matched filter detection (Shobana et al, 2013), energy detection (Zhang et al, 2009; Zhai, 2007) and cyclostationary detection (Sutton et al, 2008; Turunen et al, 2009). In cooperative sensing, multiple SUs cooperate with each other, in a centralized or distributed mode, to determine the channel availability (Song et al, 2012).

The common local sensing model is referred to as a two-state model. That is, there are two distinct channel states: idle and busy. Specifically, it is defined as below with energy detection (Oh et al, 2009):

$$x_i = \begin{cases} n_i, & \text{idle} \\ s + n_i, & \text{busy} \end{cases}$$

where, $x_i$ is the signal that SU $i$ receives, $n_i$ is the zero-mean Additive White Gaussian Noise (AWGN), $(s)$ is the signal that the PU transmits. In our paper, we follow this two-state sensing model and take it into account while considering the interference model.

Interference plays a critical role in CRNs, especially in a wireless transmission environment. In (Hong et al, 2008), the distribution of the interference power at a primary receiver was studied when the interfering SUs follow a Poisson field distribution. They found that the interference probability density functions (PDFs) follow heavy-tailed $\alpha$-stable distributions. In (Chen et al, 2010), an interference model with power or contention control was further presented. In (Rabbachin et al, 2011), the authors propose a statistical interference model. They consider the sensing procedure, secondary spatial reuse protocol, path loss, shadowing, and channel fading, etc. A statistical model is developed by
using the theory of truncated-stable distributions. Most of the existing models and related analysis are significantly complex.

In our paper, we fully consider spectrum sensing into interference analysis and propose a simple probabilistic model for interference at PUs due to SUs in a CRN. With the two-state sensing model, SUs can only use a channel when in *idle state*. In other words, if any user is occupying the channel, other SUs are prohibited from concurrently transmitting on the same channel. Therefore, with this sensing model, the SUs that detect an active user in their sensing range do not participate in transmission. This observation will significantly simplify interference modeling and analysis due to the bounded maximum number of interfering SUs, which will be studied in detail in the subsequent sections.

3. System Model

As the system model, a wireless ad hoc CRN shown in Figure 1 is considered. There is one PU communication pair consisting of a transmitter (*Tx*) and a receiver (*Rx*). One licensed channel is assigned to this PU pair. At the same time, multiple SUs are allowed to access the same channel when it is sensed idle. Due to the limited sensing range, however, SUs might not accurately sense state of the channel. It is worth noting that inaccurate sensing may result by other factors such as severe noise and a specific sensing approach. For the sake of simplicity, we assume that the false sensing merely come from the limit of sensing range of SUs. Therefore, SUs that are outside the sensing range of PU *Tx* but inside the sensing range of PU *Rx* may not accurately detect the active PU transmission. Therefore, those SUs may communicate on the same channel simultaneously and hence cause interference to the PU receiver.

Figure 1 shows an active PU transmission and possible SU interference from the shaded region marked in red (interference zone). In other words, SU transmitters will cause interference to the PU receivers if they are located in the interference zone. As it can be seen the SUs in the interference zone are not in the sensing range of PU *Tx*, and hence cannot sense the transmission. It is worth noting that if the PU *Tx* is not active, the system simply changes to a regular wireless ad hoc network which solely consists of SUs. In this case, the interference from SUs to PUs becomes pointless. Therefore, we concentrate on the case when the PU transmission is active and then analyze the interference caused by the co-existing active SUs. Note that, only SU transmitters, rather than SU receivers, contribute to the interference on the PU receivers, so SU receivers are not shown in Figure 1.

In this system model, we make several major assumptions and they are summarized as follows:

1) **SU Distribution**: Normally, PUs are physically protected according to the FCC policies. For instance, IEEE 802.22 states that there is a protected contour of TV stations (Liu et al, 2010). In our system model, we assume *R*, the transmission range of PU *Tx*, is the radius of the protected area centered at the PU. SUs are prohibited from transmission on the same channel once they fall into PUs’ protected area. This can be implemented by using a geo-location module over TV white space (Ahuja et al, 2008). Out of the protected area, SUs are distributed randomly in a two-dimensional space with density *p*. Therefore, the average number of SUs is $N = \rho S$ with *S* as the area.
2) Channel Access: The entire channel bandwidth is assumed available for access by all SUs if they do not detect the PU transmission. SUs are assumed to be greedy so that they attempt to transmit whenever they do not sense other active users.

3) Equal Interference and Sensing Range: The interference and sensing range of PUs and SUs are denoted by $R_p$ and $R_s$ respectively. The interference range of PUs typically exceed the interference range of SUs, i.e., $R_p > R_s$ (Sharma et al, 2011). For simplicity, the interference range and the sensing range are assumed to be equal. Additionally, the interference of the PU to SUs is beyond the scope of this paper and will not be studied. Only the interference to the PU from SUs are investigated.

4) Power Loss: The received power/interference at the PU receiver, denoted by $P_r(d)$ at a distance $d$ from an SU transmitter, can be expressed as (Haykin et al, 2004):

$$P_r(d) = \frac{\beta P_t}{d^\alpha},$$  \hspace{1cm} (1)

where $P_t$ is the transmitted signal power at the transmitter, the path-loss exponent $\alpha$ is typically from 2 to 5, depending on the communication environment. $\beta$ represents the measured path loss at a reference distance $d_0$ and can be calculated as:

$$\beta = G_T G_R \left(\frac{4\pi d \beta}{\lambda}\right)^2,$$  \hspace{1cm} (2)

where $G_T$ and $G_R$ are the antenna gains of the transmitter and the receiver, respectively. $\lambda = \frac{c}{f}$ is the signal carrier wavelength.

4. Interference Modeling and Analysis

Figure 1 illustrates a simple CRN, in which one PU $Tx$, one PU $Rx$ and three SU $Txs$, denoted by SU1, SU2 and SU3 are shown. We will now examine which SUs are possible interfering users to the PU $Rx$. It can be seen that SU1 produces no interference on the PU $Rx$ because both, $Tx$ and $Rx$, are beyond its interference range. With regard to SU2, PU $Tx$ falls into the sensing range of SU2. Therefore, the presence of PU $Tx$ can be detected by SU2, therefore, SU2 is refrained from transmitting and causes no interference to PU $Rx$. Likewise, all SUs in the circular area of the radius $R_s$ centered at $Tx$ do not participate in the channel competition. In contrast, SUs are not able to detect the presence of PU $Rx$ due to no power emission. Even though SUs are situated within the circle with the radius $R_s$ around $Rx$, they cannot sense the presence of the PU $Rs$. As a result, SU3 is not aware of the existence of PU $Rx$, then transmits concurrently with the PU and thus causes interference at the PU $Rx$. In summary, the interference zone disturbed by SUs to the PU $Rx$, i.e., the shaded area in Figure 1, is the circular area of radius $R_s$ around $Rx$ that neither overlaps with the circular zone of radius $R_s$ around $Tx$ nor overlaps the protected zone of radius $R$ around $Rx$.

The interference zone is denoted by $S$ and the number of SUs in $S$ is represented as $K = N(S)$. We assume that the minimum number of interfering SUs in the interference zone is 1, as long as the area of the shaded zone is greater than 0 with an appropriate density parameter $\rho$. Note that two SUs can transmit simultaneously if they are at least 2$R_s$ (sensing range) distant apart. Therefore, the number of interfering SUs is finite. In principle, no active SUs are allowed to fall into other active users’ sensing area. Therefore, for each active SU, the minimum angle for its sensing area which overlaps with the interference zone at the PU $Rx$ is $\pi/3$ radians as shown in Figure 2. The maximum number of interfering SUs can be derived as: $\left\lceil\frac{2\pi - \alpha}{\pi / 3}\right\rceil$, where $\lceil \cdot \rceil$ is a ceiling function. In our system model, the maximum number is 4, since $\alpha < \pi / 2$, as shown in Figure 2. All cases with 1, 2, 3 and 4 interfering SUs will be considered next. The following steps depict the process.

**STEP 1:** Note that the number of SUs in $S$ is $K = N(S)$. An SU, denoted by $SU_m(m = 1, \ldots, K)$, is randomly chosen from the interference zone $S$, so the probability of choosing $SU_m$ is $1/K$. Once knowing the interference zone for the first selected user $SU_m$, the overlapping area with the interference zone is represented as $S_m$(See Fig. 3). The remaining
area from the interference zone is \( S_m = S - S_m \). If \( N(\overline{S_m}) = 0 \), then STOP. This implies that there is only one interfering SU in total. As, nodes are deployed with uniform distribution, they can be approximated as a two-dimensional special Poisson process with density \( \rho \), therefore, the probability of \( N(\overline{S_m}) = 0 \) can be calculated as:

\[
P(\overline{S_m}, 0) \triangleq \Pr\{ \text{zero user in } \overline{S_m} \} = \exp(-\rho \overline{S_m})
\]

(4)

**Figure 2. Illustration of the maximum number of interfering SUs**

From the above, the probability of having only one interfering SU is:

\[
P(S, 1) \triangleq \Pr\{ \text{only 1 interfering SU} \} = \sum_{m=1}^{K} \frac{1}{K} \times [\exp(-\rho \overline{S_m})]
\]

(5)

The interference to the PU \( R_x \), represented by \( I \), can be obtained by: \( I = I_1 \), where \( I_1 \) is calculated according to Eq. 1. Else if \( N(\overline{S}_1) \neq 0 \), there can be more than one SU interferers, hence, GO TO NEXT STEP

**STEP 2:** With spectrum sensing, no other SUs in the \( S_m \) are allowed to become active simultaneously. The second interfering user can only be selected from the remaining area \( \overline{S_m} \), from which the second interfering SU \( \tilde{S}_m \) is selected. Let the remaining area be \( \overline{S_m} = S - S_m - S_n \). Assume that the number of SUs in the remaining area \( S_m \) is represented as \( K_m = N(\overline{S_m}) \). If \( N(\overline{S}_m) = 0 \), only two interfering SUs exist, then STOP. Fig. 3 shows an example of two interferers. Accordingly, the probability of having only two interfering SUs is derived as:

\[
P(S, 2) \triangleq \Pr\{ \text{only 2 interfering SU} \} = \sum_{m=1}^{K} \sum_{n=1}^{K_m} \frac{1}{K} \times \frac{1}{K_m} \times [\exp(-\rho \overline{S_m})]
\]

(6)

If \( N(\overline{S}_m) \neq 0 \), more than two interferers, GO TO STEP 3.

**Figure 3. One example of 2 interfering SUs.**

**STEP 3:** From the remaining area \( \overline{S_m} \), the third interfering SU \( j \) is randomly selected. Plot the interference range for \( SU_j \) and the overlapped area: with the shaded zone represented as \( S_j \). The remaining area after choosing three interfering SUs can be denoted by \( \overline{S_m} = S - S_m - S_n - S_j \), where \( m, n, j = 1, ..., K \). The number of SUs in \( \overline{S_m} \) is represented by \( K_{mn} = N(\overline{S_m}) \). If \( N(\overline{S_m}) = 0 \), then STOP. This implies the maximum number of interference SUs is 3. An example is shown in Figure 4. Similarly, \( P(S, 3) \) can be derived as:

\[
P(S, 3) \triangleq \Pr\{ \text{only 3 interfering SU} \} = \sum_{m=1}^{K} \sum_{n=1}^{K_m} \sum_{j=1}^{K_{mn}} \frac{1}{K} \times \frac{1}{K_m} \times \frac{1}{K_{mn}} \times [\exp(-\rho \overline{S_m})]
\]

(7)

The interference to the PU \( R_x \), can be obtained from: \( I = \sum_{i=1}^{3} I_i \), where \( I_i (i = 1, 2, 3) \) is determined from Eq. 1.
If \( N(\bar{S}_{123}) \neq 0 \), GO TO STEP 4.

**STEP 4:** From the remaining area \( \bar{S}_{\text{mnj}} \), the fourth interfering user SU4 is randomly selected. Since the maximum number of interfering SUs is 4, \( S_1 + S_2 + S_3 + S_4 = S \) holds. The interference to the PU RX, can be obtained by: \( I = \sum_{i=1}^{4} l_i \), where \( l_i \) \( (i = 1, 2, 3, 4) \) is calculated according to Eq. 1. The probability of having 4 interfering SU is:

\[
P(S, 4) = \text{Pr} \{ \text{interfering SU is 4} \} = 1 - P(S, 1) - P(S, 2) - P(S, 3)
\]

A example of four interferers is shown in Fig. 5.

From the above steps, the interference power at the PU RX for each case is obtained. The signal to noise ratio (SNR) and signal to interference-plus-noise ratio (SINR) can be corresponding obtained as:

\[
\text{SNR} = \frac{P_{PR}}{P_N}; \text{SINR} = \frac{P_{PR}}{I+P_N}
\]

where, \( P_{PR} \) is the received power at the PU RX from the PU TX, \( P_N \) is the noise power, \( I \) is the interference power and can be obtained depending on the number of total interfering SUs.

5. Simulation Results

In this section, through our extensive simulations using MATLAB we investigate and evaluate the interference from SUs at the PU RX. We also observed the change in the signal to noise ratio (SNR) with the introduction of interference. Moreover, the probabilities of \( k \) \( (k = 1, 2, 3 \text{ and } 4) \) interfering SUs are also calculated. In the simulation model a PU TX is transmitting to a PU RX and numerous SUs are randomly distributed in the two-dimensional area with node density of \( \rho = 0.021 \). Transmission range or protection radius of the PU TX and RX is \( R = 30m \) and other SUs placed within this protected area are not allowed to transmit during the ongoing transmission. Average number of neighbors \( N = 60 \). Free path wireless transmission parameters used in Eq. 1 and 2 are: \( \alpha = 3 \), \( G_T = G_R = 1 \), \( d_0 = 1 \), \( f = 900MHz \), \( P_{T_P} = 6.9dBm \) and \( P_{T_S} = 3.9dBm \) are the fixed transmit power of PUs and SUs, respectively. The channel is modeled as Additive White Gaussian Noise (AWGN) and the noise power is set to -80 dBm.

In the first scenario, we observe the effect of distance \( D \) between the PU TX and RX on the interference power received at PU RX. From Fig. 6, we observe that the interference power steadily increases with \( D \). This result is in good agreement with its physical interpretation. As we observe, the area of the interference zone (shaded area in Fig. 1) constantly increases as \( D \) increases from 5m to 30m and its maximum is reached at \( D = 30m \). This is because the transmission range of the PU TX is 30m. In other words, increased interference area leads to a higher number of interfering SUs.
**Figure 6. Interference power received at the PU Rx varies with the PU Tx-Rx Euclidian distance.**

Fig. 7 shows the comparison between the average SNR and SINR at the PU Rx. It is observed from the plots that significant interference is caused by the SUs. For example, SINR decreases approximately 7 dB in comparison with SNR at D=30m. In other words, with an acceptable signal level (threshold) of 6.4 dB it can be observed that the range for an acceptable SNR that is achieved at 30m becomes 17m by considering interference (i.e., SINR). Therefore, to achieve an acceptable SINR, the transmission range should be reduced or transmit power should be increased.

**Figure 7. Comparison between SINR and SNR with PU Tx-Rx Euclidian distance changes.**

In the third scenarios, the probability of interference from $k$ SUs, where $k = 1, 2, 3, 4$ is shown in Fig. 8. This figure depicts that the probability of having two interfering SUs is generally higher than in any other case, except after $D=25m$ when probability of having three interferers becomes the highest. This is because a short distance $D$ means the interference zone is relatively small and hence almost two interfering SUs will cover the entire interference zone. However, as the distance increases, the area of the interference zone becomes larger and hence in the case when $D \geq 25m$ the likelihood of having three interferers increases significantly. Note that, although theoretically there can be a fourth interferer, the probability of four interferers is negligibly small, as the remaining exclusion region for the fourth interferer is considerably smaller.

**Figure 8. Probability of $K$ ($K=1, 2, 3, 4$) interfering SUs varies with Euclidian distance.**

We have also considered scenarios where the SU node density (average number of SUs) varies while keeping the distance between PU Tx and Rx as a constant. For example, in Fig. 9, interference power at the PU Rx is shown. The increase in power is because as the SUs’ traffic increase, probability of having more interferers also increases.

**Figure 9. Interference power received at the PU Rx varies with the average number of neighbors, $D=30m, R=30m$.**
Fig. 10 shows the difference between SNR and SINR with changing number of SUs. SNR plot remains constant as it does not take into account the interference power. SINR, however, decreases with SU users as the probability of SU interferers’ increases.

![Graph showing comparison between SINR and SNR](image)

**Figure 10.** Comparison between SINR and SNR with average SU neighbors changes, $D=30m$, $R=30m$

**Conclusions**

Interference to PUs caused by SUs is a critical issue in CRNs. We have used a two-state spectrum sensing model and proposed a relatively simple probabilistic interference model. We have shown that, the maximum number of simultaneously interfering secondary users is bounded, typically ranging from 1 to 4. We have demonstrated all the cases with possible interfering secondary users. The probability for each case was derived. Extensive simulations and results have verified the effectiveness and accuracy of the proposed approach.

**Acknowledgement**

The research of this paper is supported in part by NSF under grant ECCS-1310562 and NASA under grant NNX12AI3A.

**References**


---

Dr. Yanxiao Zhao is Assistant Professor in the Electrical and Computer Engineering Department, South Dakota School of Mines and Technology, SD, USA. She received her Ph.D. degree in Electrical and Computer Engineering from Old Dominion University, USA, in 2012. Her research interest primarily lies in wireless communications and networking. She was the recipient of the Best Paper Award in WASA 2009. Dr. Zhao is currently serving as an Editor for International Journal of Research and Reviews in Ad Hoc Networks (IJRRAN), TPC member for several international conferences such as ICCCN, WiCOM, WASA and ICNC. She is also a technical reviewer for dozens of international journals and conferences.
Dr. Bighnaraj Panigrahi is a Research Scientist-I with the department of Electrical and Computer Engineering, South Dakota School of Mines and Technology, SD, USA. He received his B. Sc. degree in Physics and M. Sc. degree in Electronic Science in 2001 and 2004 respectively from Berhampur University, India, M.Tech. degree in Computer Science in 2007 from Utkal University, India. He received his Ph.D. degree in Electrical Engineering from IIT Delhi, India in 2012. His major research interest includes wireless sensor and ad hoc networks, performance optimization, cross layer techniques in wireless networks. He is the author and co-author of several international conferences and journals.

Dr. Kazem Sohraby is Professor and Head of Electrical and Computer Engineering Department at South Dakota School of Mines and Technology. He also served as Professor and Head of Department of Computer Science and Computer Engineering, and Professor of Electrical Engineering in the College of Engineering, University of Arkansas at Fayetteville, AR. Prior to joining University of Arkansas, he served as the chair of Interdisciplinary Telecommunications Management department at Stevens Institute of Technology. He was with the Mathematical Sciences Research Center, Mathematics of Networks and Systems, and with the Performance Analysis Departments (Advanced Communications Technologies) at Bell Labs (Lucent Technologies, and AT&T). He is founder of Center for Advanced Computing and Communications Research, and Networking Research, College of Engineering, University of Arkansas, and is a Principal Consultant on Defense Information Systems Agency (DISA) projects. His areas of interest include computer networking, signaling, switching, performance analysis, and traffic theory. He has over 20 pending and granted patents on computer protocols, wireless and optical systems, circuit and packet switched computer networks, and Optical Internet. He has over 60 publications and book chapter contributions, and is co-author of a book on the performance and control of computer communications networks. He currently serves as an IEEE Communications Society Director and served as its president's representative on Committee on Communications and Information Policy (CCIP), and has been a Distinguished Lecturer of that Society 1996 - 2005. He served as chair of several conferences in both ACM and IEEE. He also served on the education committee of the IEEE Communications Society, is on the editorial boards of several publications, and panelist and reviewer with the National Science Foundation, US Army, and Natural Sciences and Engineering Research Council of Canada. He received PhD, MS, and BS (high honors) all in Electrical Engineering, and his MBA from the Wharton School, University of Pennsylvania.

Dr. Wei Wang is an Assistant Professor with the department of Electrical Engineering and Computer Science, South Dakota State University, Brookings, SD, USA. He received his B.S. degree in Computer and Information Engineering from Xian Jiaotong University, China, 2002, and M.S. degree in Information and Communication Systems from Xian Jiaotong University, China, 2005. He received his Ph.D. degree in Computer Engineering from University of Nebraska - Lincoln, USA, 2009. His major research interests include wireless sensor networks, multimedia computing, information security, and educational robotics. He won 2 Best Paper Awards of IEEE WCNC 2008 and ANSS 2011. He serves as an Associate Editor of Wiley Security in Communication Networks Journal, the Guest Editor of three Special Issues for Hindawi IJDSN on Energy-Efficient Sensor Networks, Underwater Wireless Sensor Networks, and Data Dissemination in Vehicular Environments, the workshop co-chair of ICST BodyNets 2013, the program vice chair of ACM RACS 2013, the chair of IEEE CIT-MMC track 2012, the vice-chair of IEEE ICCT-NGN track 2011 and the program chair of the ICST IWMMN 2010, and a Technical Program Committee (TPC) member for many international conferences such as IEEE GLOBECOM, ICC and WCNC.