MULTIMEDIA COMMUNICATIONS TECHNICAL COMMITTEE
IEEE COMMUNICATIONS SOCIETY
http://www.comsoc.org/~mmc

E-LETTER

Vol. 7, No. 6, July 2012

IEEE COMMUNICATIONS SOCIETY

CONTENTS

Message from MMTC Chair

Dear MMTC fellow members,

This is the first time that I am writing to you as the Chair of MMTC. I want to thank all of you for contributing to the fast growth and success of MMTC during the past years, especially in the past two years during which I served as Vice Chair of MMTC. Special thanks go to our past Chair, Dr. Haohong Wang, who has made MMTC a very strong community through his great leadership.

I am also very happy to introduce you the new MMTC officers (elected during ICC'2012) for the term of 2012-2014:

- TC Chair, Jianwei Huang (The Chinese University of Hong Kong, Hong Kong)
- Steering Committee Chair, Pascal Frossard (EPFL, Switzerland)
- TC Vice Chair – Letters & Member Communications, Kai Yang (Bell Labs, USA)
- TC Vice Chair – North America, Chonggang Wang (Interdigital, USA)
- TC Vice Chair – Asia, Yonggang Wen (Nanyang Technological University, Singapore)
- TC Vice Chair – Europe, Luigi Atzori (University of Cagliari, Italy)
- TC Secretary, Liang Zhou (Nanjing University of Posts and Telecommunications, China)

The new team has a good diversity in terms of technical backgrounds, experiences, and geographical locations. All of them have been very active in the MMTC leadership team during the past years. The team will work together to provide the best service to the community.

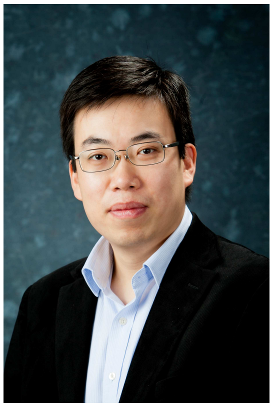
In the next two years, we will continue the development of MMTC and try to reach an even higher standard. Our TC has been growing into a large community with 1500 members, with strong presence in ComSoc conferences, journals, and other technical activities. We will build upon this strength, and further increase the visibility of the TC and provide better services to the community. Here are several thoughts on the future directions.

- Keep expanding and supporting MMTC sponsored high quality conferences and workshops in major venues (ICC/GC/ICME/INFOCOM).
- Continue improving the quality of the now very popular E-letter and R-letter. Attract more substantial submissions through invited special issues and open calls, with focus on emerging new topics.
- Increase the visibility and impact of MMTC in major ComSoc journals, through special issues, editorship, and involvement in steering committees.
- Help members in IEEE membership promotions (to senior member and fellow grades), by providing support letters that faithfully represent the candidates' contributions to the MMTC.
- Strengthen the service e-platform so that more members will use and benefit. Provide high quality research idea exchanges through MMTC Distinguished Talk Program.

This will be an evolving list, and I look forward to hearing your great suggestions as always.

Last but not least, MMTC's next meeting will be held in ICME 2012, Melbourne, Australia (http://www.icme2012.org/). The tentative time and location of the meeting will be 12:10 - 13:20, July 10, room 112 of the conference location. Please check the conference for updated information on July 10 again, and we look forward to seeing you there.

Regards,



Jianwei Huang

Chair of Multimedia Communication TC of IEEE ComSoc

SPECIAL ISSUE ON "Multimedia Communications in Cognitive Radio Networks"

Multimedia Communications in Cognitive Radio Networks

Fen Hou, Macau Polytechnic Institute, China
{fhou}@ipm.edu.mo

Cognitive radio network and technology has been attracting many attentions from both industries and academia. From spectrum sensing, MAC protocol design, to service differentiation and quality of service provisioning, there are many key challenges and open issues to be addressed in these research areas. This Special Issue collects six selected papers that present various discussions on different aspects for achieving the success of cognitive radio network and technology.

Spectrum sensing is an important block in the successful deployment of cognitive radio networks. The first two papers "Spectrum Sensing with Uncertainty in Cognitive Radio Networks" and "Low Complexity Optimal Sensing Strategy for Maximized Throughput in Cognitive Radio Networks" focus on this topic. The first one discusses the impacts of the parameter uncertain and the potential mismatch of the primary signals' distribution on the accuracy of spectrum sensing. By formulating the sensing design into a robust optimization problem, this paper introduces the research results in terms of lower bound of the detection probability in the scenarios with/without multi-user cooperation. The second paper considers a cooperative sensing scenario. This paper applies the hard combining fusing rule in the problem formulation. By jointly optimizing the sensing time and the fusion parameter, the proposed method aims to maximize throughput of secondary users as well as providing sufficient protection for the primary users.

The third paper "Spectrum-aware QoS MAC for Multimedia Services in Cognitive Radio Networks" proposes a distributed MAC for supporting real-time applications. By effectively selecting the sensing channel and carefully determining the sensing windows, the proposed MAC mechanism can provide distinct quality of service for different types of traffic. The provisioning of service differentiation makes the proposed MAC mechanism be capable of supporting heterogeneous multimedia applications in cognitive radio networks.

The fourth paper "Sora-based Cognitive OFDMA Wireless Communication System" focuses on the design and implementation of orthogonal frequency division multiple access (OFDMA) based cognitive radio system. The paper introduces the Sora-based cognitive radio system in detail including the system architecture, the process of signaling exchange, and the whole communication process. Test results are also presented to show the good performance of this system in terms of reliable sensing and robust communications.

The fifth paper "Playing Games in Cognitive Radio Networks" introduces recent game theoretic results about the cognitive radio networks from three aspects based on three types of interactions: the interactions between secondary users (SUs), the interactions between primary users (PUs), and the interactions between both SUs and PUs.

The last paper "Applications and Opportunities for Cognitive Radio and Networks" discusses the potential prospective of cognitive radio network and technology. This article presents emerging application areas, opportunities for whitespace usage beyond the UHF band, and regulatory policy changes.

Fen Hou has been a lecturer in the Joint Research Center in Ubiquitous Computing at the Macao Polytechnic Institute in Macao from 2011. She received the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Canada, in 2008. She worked as a postdoctoral fellow in the Electrical and Computer Engineering at the University of

Waterloo and in the Department of Information Engineering at the Chinese University of Hong Kong from 2008 to 2009 and from 2009 to 2011, respectively. Her research interests include resource allocation and scheduling in broadband wireless networks, protocol design and QoS provisioning in cognitive radio network, and mechanism design in participatory sensor networks. Dr. Hou is the recipient of IEEE GLOBECOM Best Paper Award in 2010, as well as the Distinguished Service Award in IEEE ComSoc Multimedia Communications Technical Committee (MMTC) in 2011.

Dr. Hou has served as a co-chair of IEEE MMTC, as well as a technical program committee member for IEEE WiOpt 2012, IEEE ICC 2011, IEEE WCNC 2011, IEEE GLOBECOM 2010, etc. Dr. Hou has also served as a technical reviewer for IEEE Transactions on Wireless Communications, IEEE Transactions on Vehicular Technology, IEEE Journal on Selected Areas in Communications, IEEE INFOCOM, etc.

Spectrum Sensing with Uncertainty in Cognitive Radio Networks

Shimin Gong and Ping Wang, Nanyang Technological University, Singapore
{gong0012, wangping}@ntu.edu.sg

1. Introduction

Cognitive Radio (CR) [2] is proposed as a promising technique to improve spectrum utilization. In a CR system, secondary users (SUs) are allowed to access the licensed spectrum bands when they are temporarily unoccupied by primary users (PUs). A key technology to achieve this is spectrum sensing, where SUs determine the presentence of PUs based on the characteristics of the measured signals on the channels. Generally, spectrum sensing is formulated as a hypothesis testing problem, which takes measured signal samples (possibly embedded with primary signals) as inputs and draw a decision by comparing the samples with a pre-designed decision threshold.

The detection performance is usually measured by the receiver operating characteristic (ROC), representing the trade-off between detection probability (i.e., probability of sensing a busy channel as busy) and false alarm probability (i.e., probability of sensing an idle channel as busy). To study the detection performance, existing results usually assume that the received primary signal follows a Gaussian distribution, and express the detection probability in the Q-function (tail probability of the standard normal distribution) [3], [4]. Some other works analyze it through deterministic optimization problems [5], [6]. However, most of the existing studies assumed that the statistical features of the PUs' signals received at SUs' receiver are precisely known beforehand, e.g., following Rayleigh, Nakagami, or Rician distributions.

Unfortunately, such precise knowledge regarding the signals' distribution is a very strong assumption, and not necessarily leading to more reliable decisions due to several reasons as follows:

1) Complexity in real systems: It is often very complicated to model a realistic distribution for the received PUs' signals in a closed-form without significant simplifications. Even if a precise characterization is possible, a complex form makes it very had to find an explicit expression for the detection probability.

2) Mismatch: deterministic assumption about the primary signals' distribution may not always match the real situation when spectrum environment fluctuates. For example, the received signals exhibit different distributions depending on whether there is line-of-sight between transmitter and receiver. Uncertainty may also occur during the estimation of distribution parameters such as mean and variance due to channel state fluctuations.

2. Related Works

Few works considered the issues of uncertainty and robustness in cognitive radio networks. The authors in [7] proposed a probabilistic method that extracts unchanging characteristic in noise signal, i.e., information entropy. Such entropy-based method shows robustness against noise power fluctuation, but it assumed the Gaussian distribution for both noise and primary signal. In [8] the authors proposed a nonparametric cyclic correlation detector to achieve robustness when the noise statistics are not fully known. It does not require explicit assumptions on the data or noise distributions, but requires extra knowledge about the cyclic frequency of the primary system. Regarding the distribution uncertainty, two models in [9] were defined for different hypotheses in the spectrum sensing. But the detection performance was only investigated for single user case. Robust design for multi-user cooperative sensing was also considered in [10], which presented a heuristic algorithm for the threshold update.

Besides the distribution uncertainty in spectrum sensing, some other uncertain factors are also taken into consideration for system design. For example, power control of the cognitive radio system is another critical issue in managing the interference to primary system. SUs' power level is required to dynamically adjust according to PU's behavior and the channel state. In most of the cases, SUs need to estimate these channel information independently, therefore uncertainty will be inevitable due to various physical constraints. Authors in [11] and [12] considered the power control problem with inaccurate channel state information, and defined the uncertainty set for the channel gain in a D-Norm and ellipsoid respectively. Especially, the authors in [12] introduced the robust game model to study the power control problem. Considering the information asymmetry, robust stackelberg game [13] was proposed to study the power control for different group of users, i.e., leader and follower.

3. Robust Optimization

Robust optimization is usually employed to study the model mismatch and parameter uncertainty in practical problems. It describes the uncertain data or parameters by an uncertainty set. Given any instance of the uncertain data, robust optimization problem is degenerated to an ordinary optimization problem that can be investigated through existing methods. However, when the uncertainty set has infinity instances, a robust optimization problem is more difficult to solve than its non-robust counterpart. For a basic understanding regarding robust optimization, we can refer to [14], which also showed some techniques to compute robust solutions for specific problems. While most techniques are limited to convex optimization problems, the authors in [15] proposed an iterative descent search method for some kind of non-convex robust optimization problem. In some practical situations, data distribution (rather than data itself) is subject to uncertainty. For example, the financial time series. In this case, the robustness is formulated in a distributional robust stochastic program (DRSP) as in [16]. Moreover, the authors in [17] extended this formulation with a deviation measure that captures distributional asymmetry. Furthermore, they considered the multi-stage robust problems with recourse decisions afflinely adjustable in terms of the uncertain data in [18].

4. Spectrum Sensing with Uncertainty

We study the parameter uncertainty and potential mismatch of the primary signals' distribution, and focus on their effects on the detection performance for single user detection. Specifically, we consider the case when the statistical features (i.e., mean and variance) of the primary signals are contaminated by estimation errors, and the actual signals' distribution does not match what is often assumed in literature. To capture the uncertain distribution, we define an uncertainty set that contains all possible signal distributions whose mean and variance are close to a nominal one, and then formulate the sensing design into a robust optimization problem.

The first step is to characterize the fluctuating primary signals through an uncertainty set U. Since signal distribution is impossible to observe directly in practice, we characterize it through the mean and variance values, which are also estimated from channel observations, thus inevitably bear uncertainty. But we can obtain the primary signals' long-time averages in terms of the mean and variance, which are regarded as the *nominal* statistics. Then we estimate the range of short-time fluctuations empirically according to a specific spectrum environment. It is reasonable to assume that the instant fluctuations of mean and variance should be within small ranges to their nominal values. As shown in Fig. 1, the dash line plots the nominal distribution which is often assumed in literature. However, the mean value of actual distribution can take any value in an interval set, and the variance uncertainty is represented by different shape of the actual distributions.

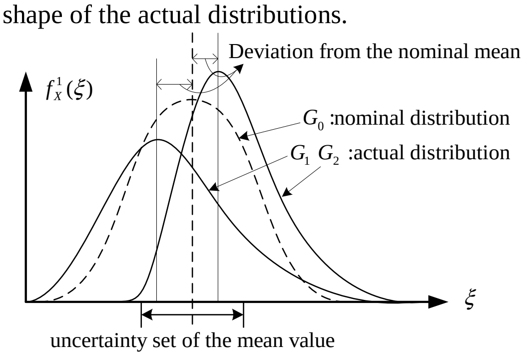


Fig. 1. An illustration of the distribution uncertainty

Given the distribution uncertainty, we are unable to find a deterministic detection probability. However, we can determine the performance bounds of the detection probability. For example, the lower bound problem is given as follows:

$$\min_{f_X^1 \in U} \int h(\xi, \lambda) f_X^1(\xi) d\xi$$

where $h(\xi, \lambda)$ returns the detection results when the received signal strength is ξ and the decision threshold is λ. The signal distribution is given as $f_X^1(\xi)$. In fact, this problem is hard to analyse directly since it involves the manipulation of function integrations (the uncertainty set U defines a series of constraints on the moment statistics which require integration over the distribution function, i.e., mean and variance statistics). To ease the analysis, we propose an equivalent transformation that eliminates the function integrations associated with the distribution uncertainty, and turns the robust problem into a maximization problem. The details can be found in [9]. This transformation provides an easy way to calculate the lower detection probability.

Our next question is whether we can achieve the extreme point of the equivalent maximization problem. We call such an optimal distribution that achieves the detection bounds as extremal distribution. We have demonstrated that a discrete distribution is an extremal distribution, and the lower bound of detection probability can be calculated through an analytical formula. However, such a result has limited significance in practice, since actual primary signal seldom exhibits a discrete distribution. Further work may consider adding the continuity into the uncertainty set for distribution function.

We further extend our work to the spectrum sensing with multi-user cooperation. In [10], we introduced the same uncertainty model into a max-min problem. This work presents an iterative algorithm that determines the robust decision thresholds for all cooperative users. The algorithm starts from an initial choice of decision thresholds that satisfies the false alarm probability constraint, and solves the rest of the problem which is in the form of semi-definite program. Then in every iteration, the algorithm searches new decision thresholds in order to improve the system objective. The final decision thresholds from this algorithm are more robust and can improve the worst-case detection performance.

4. Conclusions

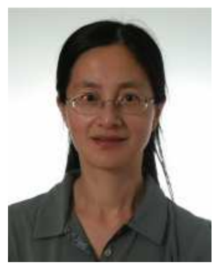
In this letter, we review the study of robust optimization in cognitive radio networks. We first illustrate some practical situations in which deterministic analysis for spectrum sensing may be inaccurate. We further present some related works in literature that consider uncertain information in spectrum sensing and power control. In particular, we apply the robust optimization techniques in spectrum sensing. Instead of a deterministic result, the robust model in single user case provides us the performance bounds of detection probability. And in the multi-user case, our model can determine the decision thresholds for all users that are more robust than existing methods.

References

[1] M. Mchenry: Spectrum white space measurements. New America Foundation Broadband Forum (June 2003).
[2] S. Haykin: Cognitive radio: brain-empowered wireless communications. IEEE Journal on Selected Areas in Communications, vol. 23, no. 2, pp. 201 – 220, Feb. 2005.
[3] A. Ghasemi and E. Sousa: Collaborative spectrum sensing for opportunistic access in fading environments. Proceedings of IEEE DySpan, Nov. 2005, pp. 131 –136.
[4] F. F. Digham, M.-S. Alouini, and M. K. Simon: On the energy detection of unknown signals over fading channels. IEEE Transactions on Communications, vol. 55, no. 1, pp. 21 –24, Jan. 2007.
[5] Z. Quan, S. Cui, and A. Sayed: Optimal linear cooperation for spectrum sensing in cognitive radio networks. IEEE Journal of Selected Topics in Signal Processing, vol. 2, no. 1, pp. 28 –40, Feb. 2008.
[6] G. Taricco: Optimization of linear cooperative spectrum sensing for cognitive radio networks. IEEE Journal of Selected Topics in Signal Processing, vol. 5, no. 1, pp. 77 –86, Feb. 2011.
[7] Jonathan Y. Zhang, Q. Zhang, and S. Wu: Entropy-based robust spectrum sensing in cognitive radio. IET Communications, vol. 4, no. 4, pp. 428–436, 5 2010.
[8] J. Lunden, S. Kassam, and V. Koivunen: Robust nonparametric cyclic correlation-based spectrum sensing for cognitive radio. IEEE Transactions on Signal Processing, vol. 58, no. 1, pp. 38–52, Jan. 2010.
[9] S. Gong, P. Wang, and W. Liu: Spectrum sensing under distribution uncertainty in cognitive radio networks. Proceedings of IEEE ICC, Jun. 2012.
[10] S. Gong, P. Wang, and J. Huang: Robust threshold design for cooperative sensing in cognitive radio networks. Proceedings of IEEE INFOCOM, Mar. 2012.
[11] G. Zheng, S. Ma, K. kit Wong, and T.-S. Ng: Robust beamforming in cognitive radio. IEEE Transactions on Wireless Communications, vol. 9, no. 2, pp. 570 –576, Feb. 2010.
[12] J. Wang, G. Scutari, and D. Palomar: Robust cognitive radio via game theory. Proceedings of IEEE Information Theory, Jun. 2010, pp. 2073 –2077.
[13] S. Parsaeefard, M.V.D. Schaar, and A.R. Sharafat: Robust Stackelberg game in communication systems. CoRR (2011)

[14] A. Ben-Tal and A. Nemirovski: Robust convex optimization. Mathematics of Operations Research, vol. 23, pp. 769–805, November 1998.
[15] K. M. Teo: Nonconvex robust optimization. Ph.D. dissertation, Massachusetts Institute of Technology, 2007.
[16] E. Delage and Y. Ye: Distributionally robust optimization under moment uncertainty with application to data-driven problems. Operations Research, vol. 58, pp. 595–612, May 2010.
[17] X. Chen, M. Sim, and P. Sun: A robust optimization perspective on stochastic programming. Operations Research, pp. 1058–1071, 2007.
[18] X. Chen and Y. Zhang: Uncertain linear programs: Extended affinely adjustable robust counterparts. Operations Research, vol. 57, pp. 1469–1482, Nov. 2009.

Shimin Gong received his B.E. and M.E. degrees from the department of Electronics and Information Engineering, Huazhong University of Science and Technology, China in 2008 and 2011, respectively. He is currently pursuing his Ph.D. in Nanyang Technological University, Singapore. His research interests include Cognitive Radio Networks and its Application, Resource Allocation in Wireless Networks, Convex and Robust Optimization techniques.



Ping Wang (M'08) received the B.E. in 1994 and M.E. degrees in 1997, from Huazhong University of Science and Technology, China, and the Ph.D. degree in 2008 from the University of Waterloo, Canada, all in electrical engineering. She is currently an assistant professor at School of Computer Engineering, Nanyang Technological University, Singapore. Her current research interests include QoS provisioning and resource allocation in multimedia wireless communications. She was a co-recipient of a Best Paper Award from IEEE ICC 2007. She is an Editor of IEEE Transactions on Wireless Communications, EURASIP Journal on Wireless Communications and Networking, and International Journal of Ultra Wideband Communication and Systems.

Low Complexity Optimal Sensing Strategy for Maximized Throughput in Cognitive Radio Networks

Rozeha A. Rashid, A. Hadi Fikri A. Hamid, N. Fisal, M. A. Sarijari, Universiti Teknologi Malaysia
{rozeha, sheila, adib_sairi}@fke.utm.my, hadifikri@gmail.com

1. Introduction

In order to enable spectrum-aware communication protocol in a cognitive radio network (CRN), spectrum sensing becomes the key technology for unlicensed or cognitive users (CUs) to exploit the unused spectrum of primary users (PUs) via opportunistic spectrum access (OSA). A longer sensing time will result in a higher detection probability (P_d) and lower false alarm probability (P_f) for a better protection of the PUs and greater opportunistic access for CUs, respectively. However, in a fixed frame size, this leads to reduced data transmission time and hence, decreases the achievable throughput of CUs.

In this paper, this sensing-throughput tradeoff is addressed under distributed cooperative sensing scenario using hard combining fusion schemes to determine the presence of PUs. An optimization formulation is developed to jointly optimize the sensing time and the fusion parameter *k* of *k*-out-of-*N* rule to achieve maximized throughput for CUs while sufficiently protecting the PUs.

2. System Model

In this work, we consider CU to operate in a frame-by frame basis. The structure consists of sensing slot with duration T_s and transmission slot with time T_t. The sensing task is executed at the beginning of the frame to assess the status of a channel whether it is active or idle. If the channel is idle, CU will transmit to its intended receiver in the remaining duration of a frame. At the end of the frame, if PU is detected, CU's data transmission will be ceased to protect the PU from harmful interference. Otherwise, CU will access the frequency band again in the next frame. The process is repeated. Obviously, the frame duration is given by;

$$T_f = T_t + T_s \tag{1}$$

The utilization of licensed channel by PU follows a Markov chain process of exponential ON/OFF states. During the ON period, generated packets of PU is transmitted immediately on the channel.

For our framework of cooperative sensing, there are several assumptions considered [1]:

- Cooperating CUs share the sensing data in a distributed network. Cooperating CUs individually perform local sensing and report the results to the CU which requests the information.
- For PU detection, energy detector is used at each CU in a distributed system as it has low computational and implementation complexities and requires no knowledge on PU's features such as modulation and frame format.
- CUs are synchronized and they sense PU in the same spectrum segments
- All exchanged information among CUs reaches its destination succesfully and noiselessly
- The exchanging process does not cause any interference to channel environment
- Each CU has an embedded knowledge database. Hence, each can function as the fusion center. In cooperative sensing, knowledge database can assist in enhancing detection performance by providing accumulated knowledge and learned experiences such as from statistical models. It also eases the processing burden of cooperative sensing by providing radio information such as PU profiles and optimal cooperative gain maps.

3. Hard Decision Fusion Rules

The implementation of hard decision rules is by making decision whenever at least *k* of *k-out-of-N* rule local decisions indicate PU is present. Assuming that there are *N* identical and independent CUs in the cooperative spectrum sensing system, the cooperative probability of detection Q_d and probability of false alarm Q_f are given by [2]:

$$Q_d = \sum_{i=k}^{N} \binom{N}{i} P_{di}{}^{i} (1 - P_{di})^{N-i} \tag{2}$$

$$Q_f = \sum_{i=k}^{N} \binom{N}{i} P_{fi}{}^{i} (1 - P_{fi})^{N-i} \tag{3}$$

where P_{di} and P_{fi} are respectively the probability of detection and probability of false alarm of each individual CR node.

If k = 1, the cooperative detection will become OR combining rule. If $k = N$, the fusion scheme is an AND rule. Half voting rule is described by evaluating $k = N/2$.

4. Formulation of Optimal Sensing Strategy

The objective function for the optimization formulation is to search for a pair of optimal T_s and k such that throughput is maximized subject to sufficient cooperative protection of PU. It is known that cooperative sensing improves detection performance and relaxed sensitivity requirements at the expense of cooperation overhead. Therefore, the formulation is developed to jointly optimize the sensing time and the fusion parameter k of k-out-of-N rule to attain the best solution for cooperative gain and incurred cooperation overhead.

In order to find the resulted normalized throughput, R_n from the cooperative sensing, the parameters of Q_d, k, N and signal-to-noise ratio (SNR) are utilized in the following steps:

1. Calculate P_{di} for the given Q_d, k and N using (2). P_{di} can be computed using an optimizer for every k and N.
2. P_{fi} is calculated using the above P_{di} :

$$P_{fi} = Q\left(\sqrt{2SNR+1}\, Q^{-1}(P_{di}) + \sqrt{\frac{T_s}{0.9}}SNR\right) \tag{4}$$

3. Q_f is then obtained using (3).
4. Finally, normalized throughput, R_n due to cooperative sensing is given by [3]:

$$R_n = \left(1-\frac{T_s}{T_f}\right)\left(1-Q_f\right) \tag{5}$$

From the optimization viewpoint, (5) is a low complexity problem as it is a unimodal function [2] with only two dimensions.

In this work, it is assumed that the CUs belong to the same cluster. Hence, the distances between them are small. Therefore, the received PU signal at each CU experiences almost identical path loss [4]. It is reasonable then to treat the SNR of step (2) as mean $\overline{SNR}$. The optimization problem is then designed to optimize T_s and k to achieve maximized R_n given N, Q_d and mean $\overline{SNR}$.

For any given T_s and k, the optimization problem is

$$\begin{aligned} &\max_{T_s,k}: R_n(T_s,k)\\ &\text{s.t.: } 0 \le T_s \le T_f\\ &\qquad 1 \le k \le N\\ &\qquad Q_d = 90\% \end{aligned} \tag{6}$$

5. Results and Discussion

The following parameter settings are from real experimental set-up; frame duration (T_f) of 224.25 ms, sampling time of 0.9 ms and initial sensing time (without optimization) of 31.59 ms [5]. The target Quality of Service (QoS) is Q_d of 90% and Q_f of less or equal to 10%. As observed from Table 1, stand alone CU system performs badly at SNR of 0.3 (-5.23 dB). The obtained T_s of 64.56 ms and Q_f of about 18% do not comply with the set constraints of T_s less than 31.59 ms and respective Q_f of less than 10%. All fusion rules perform better than the stand-alone CU. However, at -5.23 dB, AND rule still does not satisfy the T_s constraint.

Table 1. Comparison of optimal sensing time derived for stand-alone and fusion schemes at N=50, SNR = 0.3 (-5.23dB).

Rules/Performance	T_s(ms)	Q_f	R_n
Single User	64.56	0.179	0.585
AND Rule	44.64	0.033	0.774
OR Rule	12.08	0.029	0.919
Half Voting Rule	5.58	0.004	0.971
Optimal k Rule (k=12)	4.19	0.004	0.977

The cooperation gain in terms of throughput, reduced sensing time and sensing overhead achieved by optimal k rule outperform all fusion schemes. Compared to half-voting rule, optimal k rule gives an improved normalized throughput and sensing time by about 0.6% and 25%, respectively. The Q_f is comparable for both rules. More importantly, optimal k rule produces less sensing overhead as only 12 cooperating number of users (k =12) out of 50 users are needed for decision-making of the presence of PU. While for half-voting rule, 25 out of 50 cooperating CUs are required to reach a similar decision.

6. Conclusion

The issue of sensing-throughput tradeoff in a distributed cooperative sensing scenario is studied. The findings show optimizing both the sensing time and the decision making parameter *k* of *k*-out-of-*N* rule outperforms the common fusion schemes of OR, AND and half-voting rules significantly in terms of achievable throughput and reliability. The low complexity optimization framework contributes significantly towards an energy efficient system with reduced sensing time and incurred sensing overhead.

References

[1] Ian F. Akyildiz, Brandon F. Lo, Ravikumar Balakrishnan. Cooperative spectrum sensing in cognitive radio networks. In Journal of Physical Communication 4 (2011) 40-62. Elsevier.

[2] Y.-C. Liang, Y. Zeng, E. C. Y. Peh, and A. T. Hoang. Sensingthroughput tradeoff for cognitive radio networks. IEEE Trans. Wireless Commun., vol. 7, no. 4, pp. 1326-1337, Apr. 2008.

[3] Y.-C. Liang, Y. Zeng, E. C. Y. Peh, and A. T. Hoang. Sensingthroughput tradeoff for cognitive radio networks. In Proceeding of IEEE ICC 2007, Glasgow, Jun 2007

[4] W. Zhang, R. Malik, K. Letaief. Optimization of cooperative spectrum sensing with energy detection in cognitive radio networks. IEEE Transactions on Wireless Communication 8 (12) (2009) 5761-5766

[5] M. Adib Sarijari, Rozeha A. Rashid, N. Fisal, A. C. C. Lo, S. K. S. Yusof, N. H. Mahalin, Dynamic Spectrum Access Using Cognitive Radio Utilizing GNU Radio and USRP, WWRF26, Doha, Qatar, 11-14 Apr 2011

Rozeha A. Rashid received her B.Sc. in electrical engineering from the University of Michigan, Ann Arbor, and her M.E.E. in telecommunication from the Universiti Teknologi Malaysia (UTM) in 1989 and 1993, respectively. She is a senior lecturer in the Department of Telematics and Optics, UTM. She is currently pursuing her Ph.D. in the field of Cognitive Radio (CR). Her current research interests include wireless communications, sensor network, ultra wideband (UWB), and CR.

Norsheila Fisal received her B.Sc. in electronics communication from the University of Salford, Manchester, United Kingdom, in 1984, M.Sc. in telecommunication technology, and Ph.D. in data communication from the University of Aston, Birmingham, United Kingdom, in 1986 and 1993, respectively. Currently, she is Head of the Telematic Research Group

Mohd Adib Sarijari received his B.Eng and M.Eng (Electrical) from Universiti Teknologi Malaysia (UTM), Malaysia, in 2007 and 2011 respectively. He has been working with UTM as a tutor. He is currently pursuing his Ph.D at Delft University of Technology, The Netherlands. His research interests are Cognitive Radio, Wireless Sensor Network and Smart Grid.

Abdul Hadi Fikri Abdul Hamid is a Research Officer at Universiti Teknologi Malaysia. Prior to that, he was a fellow Master student at the same university in 2011. He received B.Eng. degree in Electric-Electronic Engineering from the Universiti Teknologi Malaysia, Malaysia in 2007. His research interests include Wireless Sensor Network, Cognitive Radio and Embedded SystemDesign

Spectrum-aware QoS MAC for Multimedia Services in Cognitive Radio Networks

Yongkang Liu, Lin X. Cai, Xuemin (Sherman) Shen (Fellow, IEEE), and Jon W. Mark (Life Fellow, IEEE)
University of Waterloo, Canada
{y257liu, lcai, xshen, jwmark}@bbcr.uwaterloo.ca

1. Introduction

Cognitive radio (CR) has been emerging as a promising solution for addressing the spectrum scarcity problem by allowing unlicensed secondary users (SUs) to explore the spectrum access opportunities for data transmissions when licensed primary users (PUs) are vacant from the medium. As the PUs access the reserved spectrum bands from time to time, the spectrum opportunities available for SUs are highly dynamic. In addition, SUs may carry multiple types of traffic which have different quality of service (QoS) requirements. Therefore, it is crucial to design an efficient spectrum-aware medium access control (MAC) protocol with QoS provisioning to allow SUs to effectively probe the available spectrum bands and share them with other SUs.

2. Distributed QoS-aware Cognitive (QC) MAC

The design of spectrum-aware CR MAC differs from that of the classic MAC protocols in the close coupling with the physical layer and the cognitive hardware support [1], e.g., spectrum access opportunity is detected by physical layer radio frequency (RF) unit and MAC layer spectrum sensing and spectrum access. As spectrum sensing is crucial in CR MAC, most of the previous works mainly focus on the design of spectrum sensing policies with/without cooperation among multiple SUs to improve the sensing accuracy while maintaining a low level coordination overhead[2][3][4].

Some recent works study QoS provisioning in CR networks in support of real time multimedia applications. Wang *et al*. [5] analyze the capacity of a voice only CR network in terms of the maximum number of voice connections that can be supported with QoS guarantee, and Feng *et al*. [6] study studies the performance of telemedicine service with real time constant bit rate traffic pattern mixed with urgent messages in an infrastructure-based CR network. In a CR network, the traffic patterns in different spectrum bands may vary depending on the activities of PUs. For example, the OFF periods in TV bands are relatively long when programs terminate, while they could be very short in cellular bands where a large number of cellular customers carry voice traffic with a very low rate. Moreover, different SUs may have various applications with different traffic characteristics and QoS demands. To efficiently probe the spectrum access opportunity for QoS provision of SUs, it is essential to consider the characteristics of both the traffic and the channel usage pattern in the MAC design.

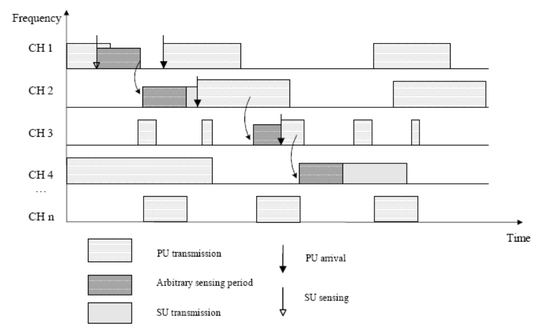


Fig. 1 Multi-channel Transmissions

We propose a distributed cognitive MAC protocol for multimedia services over CR networks. By exploiting diverse channel usage patterns, SUs select appropriate channels that satisfy their QoS requirements for channel sensing and data transmissions. The transmission procedure of an SU is shown in Fig. 1. Without loss of generality, an SU senses the first channel and starts data transmission if the channel is sensed idle for a sensing interval. To reduce possible collisions among SUs, each SU will sense the channel for an arbitrary sensing period (ASP), which consists of the basic sensing period that assures satisfactory sensing accuracy plus some random slots selected from a sensing window [0, SW_i]. If the channel is sensed busy, the SU switches to the second channel. At the beginning of the channel sensing period, the sender will initiate a handshake with its receiver over the control channel for transceiver synchronization. It is also possible that a PU may appear during SU's data transmission, in which case the transmission fails and the SU will switch to the next channel to retransmit the data. The procedure repeats until the SU exploit the spectrum access opportunity and successfully transmit the data. The key research issue in the CR MAC design is how to effectively probe the spectrum opportunities and select an appropriate set of channels to assure the QoS satisfactory of SUs, without causing undue interference to PUs.

Channel Sensing: To fully utilize the spectrum opportunity, SUs calculate the probability that the current frame can be successfully transmitted over a channel. Based on the calculated successful transmission probability in each channel, SUs can determine the channel sensing sequence with two different policies: greedy and ascending. For the greedy policy, SUs simply sort channels in a descending order and always use channels with the highest success probability for achieving a low delay and high throughput. However, the channel with less PUs' activity is more likely to be selected by SUs, which causes high contention level among SUs sharing the same radio resources and degrades the performance accordingly. Therefore, we propose the second sensing policy that allows different SUs to select various channels based on the QoS requirements of their applications. Specifically, each real-time frame is associated with the maximum tolerable one hop delay t_i. To satisfy the delay requirement, an SU should select a set of channels such that the expected transmission time over the channel is smaller than t_i. Notice that although SU can estimate the channel usage pattern by PUs, it is difficult, if not impossible, for an SU to accurately estimate the number of SUs currently sharing the spectrum bands. For a simple yet robust MAC design, an SU should set a stringent delay bound and select a channel set with more opportunities to absorb the impacts of other SUs.

Table I Sensing Window Design for Multimedia Services

	Strict Priority	Statistical Priority	No Priority
Voice	[0,31]	[0,31]	[0,31]
Video	[32,63]	[0,63]	[0,31]
Data	[64,127]	[0,127]	[0,31]

Service Differentiation: We further enhance the QoS provisioning of the proposed cognitive MAC by introducing service differentiation in the arbitrary sensing periods of different traffic flows. Basically, a smaller sensing window is applied for a higher priority real time applications so that they have a higher chance to access data channels when opportunity appears, i.e., $SW_{voice} < SW_{video} < SW_{data}$. In addition, by carefully determining the sensing windows for different types of traffic, multiple levels of QoS provisioning can be achieved for multimedia applications in CR networks. As shown in Table I, a statistical priority is provided by simply doubling the sensing windows for various types of traffic, while a strict priority can be achieved when non-overlapped sensing windows are used.

The performance of the service differentiation scheme is shown in Fig. 2. There are 10 voice (iLBC codec [7]) and 10 video (Star Trek – First Contact" trace [8]) flows in the network, and one saturated background data flow in each channel. The delay of voice traffic does not change much with the traffic loads in the network; the delay of video traffic slightly increases; while the data throughput decreases when more video SUs join in the network. By applying different sensing windows for voice, video, and data, multimedia traffic have a higher priority to be transmitted when opportunity appears. When a strict priority setting is applied, data packets have a lower probability to access the channel, and thus multimedia applications achieve a better delay at the cost of a lower throughput for data flows.

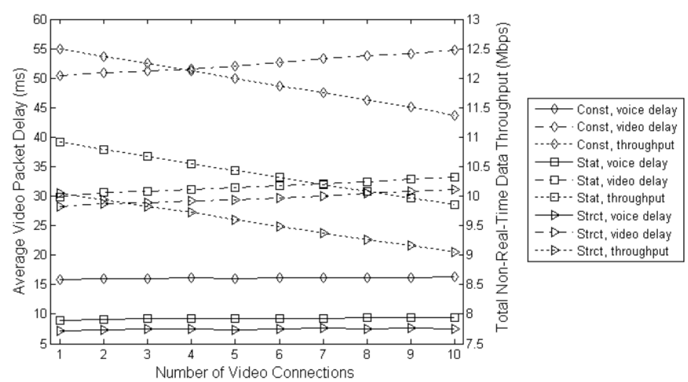


Fig. 2 Performance Comparison with Different Sensing Windows

3. Performance Analysis

We develop an analytical model to study the delay performance of the proposed CR MAC for multimedia services. An SU senses a channel and attempts to transmit if the channel is sensed idle for an ASP. During the channel sensing, an SU may fail if 1) the channel is occupied by a PU at the beginning of sensing, or 2) a PU turns on in an idle channel during the ASP, or 3) the tagged SU loses the contention due to other SUs' transmissions in channel access. SU transmits data when its sensing succeeds, or it switches to the next channel when the sensing fails. Without loss of generality, an SU checks the set of selected channels in a sequence, {CH_1, CH_2,..., CH_N, CH_1, ... }, until the packet is successfully transmitted. In [9], we have established the probability that an SU transmission succeeds in the selected channel at the r-th attempts as

$$Ps(r) = P_{TS}^{r} \prod_{j=1}^{r-1} (1 - P_{TS}^{j}) \quad (1)$$

where P_{TS}^{r} corresponds to the probability of a successful transmission over the channel in the r-th attempt. Thus, given the average time an SU uses for one transmission attempt $E[T^r]$, we can obtain the average transmission delay of an SU as

$$E[T] = \sum_{r=1}^{\infty} E[T^r] P_{TS}^{r} \prod_{j=1}^{r-1} (1 - P_{TS}^{j}) \quad (2)$$

The delay performance of the proposed cognitive MAC is shown in Fig. 3. All SUs use the same sensing window [0, 31] without service differentiation. As it is very complicated to track the number of SUs in each data channel due to highly dynamic spectrum access in CR networks, we use the average number of SUs to estimate the contention level in each channel. It can be seen that the analytical results approximate the simulation ones well. It can be seen that the average delay of voice/video traffic increases with the number of SUs. The delay of voice packets are low because small voice packets are more likely to be transmitted opportunistically when PUs are inactive. For video traffic with much larger payloads, the probability of transmission failure becomes high as a PU is more likely to turn on and interfere with the SU during a longer transmission time of a video packet. When a transmission fails, an SU will switch to the next channel for sensing and retransmission, which results in a longer delay. It is also shown that in comparison with fractional (FRC) scheme which senses the channel in the descending order of the average channel available time, the proposed QC MAC achieves much lower delay because SUs always select a proper set of channels that assure high probability of successful frame transmissions, while only the average channel utilization is considered in FRC.

4. Conclusions

In this paper, we have proposed a distributed QoS-aware MAC with service differentiation for cognitive radio networks in support of heterogeneous multimedia applications. We have demonstrated that the proposed MAC provides satisfactory QoS support for multimedia services.

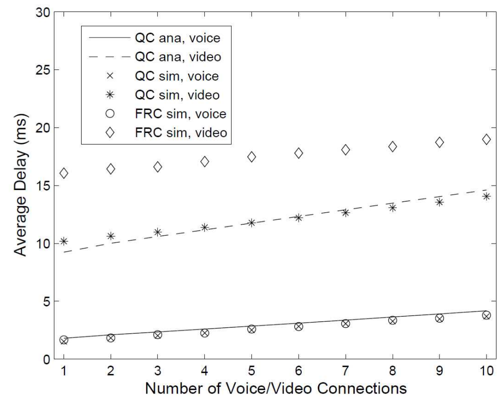


Fig. 3 Average Delay of Voice/Video Flows

References

[1] C. Cormio and K. R. Chowdhury, “A Survey on MAC Protocols for Cognitive Radio Networks,” Ad Hoc Networks, vol. 7, no. 7, pp. 1315-1329, 2009.

[2] J. Jia, Q. Zhang, and X. Shen, “HC-MAC: A Hardware-Constrained Cognitive MAC for Efficient Spectrum Management,” *IEEE J. Sel. Area Comm.*, vol. 26, no. 1, pp. 106 -117, 2008.

[3] H. Kim and K. G. Shin, “Efficient Discovery of Spectrum Opportunities with MAC-Layer Sensing in Cognitive Radio Networks,” *IEEE Trans. Mobile Comput.*, vol. 7 no.5, pp.533-545, May 2008.

[4]A. Alshamrani, X. Shen, and L. Xie, “A Cooperative MAC with Efficient Spectrum Sensing Algorithm for Distributed Opportunistic Spectrum Networks”, J. Communications, vol. 4, no. 10, pp. 728-740, 2009.

[5] P. Wang, D. Niyato, and H. Jiang, “Voice Service Capacity Analysis for Cognitive Radio Networks,” IEEE Trans. Veh. Technol., vol. 59, no. 4, pp. 1779-1790, May, 2010.

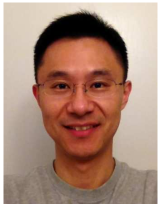
[6] S. Feng, Z. Liang, and D. Zhao, “Providing Telemedicine Services in an Infrastructure-based Cognitive Radio Network,” IEEE Commun. Mag., February, 2010.

[7] L. X. Cai, X. Shen, J. W. Mark, L. Cai, and Y. Xiao, “Voice Capacity Analysis of WLAN with Unbalanced Traffic,” IEEE Trans. Veh. Technol., vol. 55, pp.752-761, May 2006.

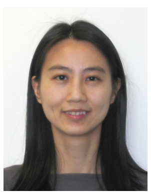
[8] Video Traces Research Group, “Video Traces for Network Performance Evaluation,” Available at http://trace.kom.aau.dk/TRACE/pics/FrameTrace/h263/indexc366.html.

[9] L.X. Cai, Y. Liu, X. Shen, J.W. Mark, and D. Zhao, "Distributed QoS-aware MAC for Multimedia

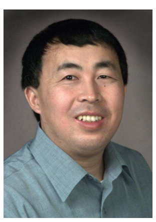
over Cognitive Radio Networks", Proc. IEEE Globecom'10, Miami, Florida, USA, Dec. 6-10, 2010.



Yongkang Liu is currently working toward a Ph.D. degree with the Department of Electrical and Computer Engineering, University of Waterloo, Canada. He is currently a research assistant with the Broadband Communications Research (BBCR) Group, University of Waterloo. His research interests include protocol analysis and resource management in wireless communications and networking, with special interest in spectrum and energy efficient wireless communication networks.



Lin X. Cai received her M.A.Sc. and PhD degrees in electrical and computer engineering from the University of Waterloo, Ontario, Canada, in 2005 and 2009, respectively. She was working as a postdoctoral research fellow at University of Waterloo. Her research interests include green communication and networking, resource management for broadband multimedia networks, and cross-layer optimization and QoS provisioning.



Xuemin (Sherman) Shen [M'97, SM'02, F'09] received a B.Sc. (1982) degree from Dalian Maritime University, China, and M.Sc. (1987) and Ph.D. degrees (1990) from Rutgers University, New Jersey, all in electrical engineering. He is a professor and University Research Chair, past Associate Chair for Graduate Studies, Department of Electrical and Computer Engineering, University of Waterloo. His research focuses on mobility and resource management, smart grid, wireless network security, e-Health, vehicular ad hoc and sensor networks. He serves as the Editor-in-Chief for IEEE Network, IET Communications, Peer-to-Peer Networks and Applications, Area Editor for IEEE Transactions on Wireless Communications, and Vehicular Technology. He is a Fellow of Engineering Institute of Canada, a registered Professional Engineer of Ontario, Canada, and a Distinguished Lecturer of the IEEE Communications Society and Vehicular Technology Society.

Jon W. Mark [M'62, SM'80, F'88] received the Ph.D. degree in electrical engineering from McMaster University in 1970. In September 1970 he joined the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, where he is currently a Distinguished Professor Emeritus. He served as the Department chairman during the period July 1984-June 1990. In 1996 he established the Centre for Wireless Communications (CWC) at the University of Waterloo and is currently serving as its founding Director. Dr. Mark had been on sabbatical leave at the following places: IBM Thomas J. Watson Research Center, Yorktown Heights, NY, as a Visiting Research Scientist (1976-77); AT&T Bell Laboratories, Murray Hill, NJ, as a Resident Consultant (1982-83); Laboratoire MASI, Universite Pierre et Marie Curie, Paris, France, as an Invited Professor (1990-91); and Department of Electrical Engineering, National University of Singapore, as a Visiting Professor (1994-95). He has previously worked in the areas of adaptive equalization, image and video coding, spread spectrum communications, computer communication networks, ATM switch design and traffic management. His current research interests are in broadband wireless communications, resource and mobility management, and cross domain interworking. A Life Fellow of IEEE, a Fellow of the Canadian Academy of Engineering, and a co-author of several books, Dr. Mark is the recipient of the 2000 Canadian Award for Telecommunications Research and the 2000 Award of Merit of the Education Foundation of the Federation of Chinese Canadian Professionals. He was an editor of IEEE Transactions on Communications (1983-1990), a member of the Inter-Society Steerig Committee of the IEEE/ACM Transactions on Networking (1992-2003), a member of the IEEE Communications Society Awards Committee (1995-1998), an editor of Wireless Networks (1993-2004), and an associate editor of Telecommunication Systems (1994-2004).

Sora-based Cognitive OFDMA Wireless Communication System

Chuangmu Yao[1,2], Lianxiang Wang[1,2], Hangguan Shan[1,2], Zhaoyang Zhang[1,2]
1. Zhejiang University, China
2. Zhejiang provincial key laboratory of information network technology, China
{yaochuanmu, qingshui1987, hshan, ning_ming}@zju.edu.cn

1. Introduction

Cognitive radio (CR) has emerged as a promising solution to mitigate the problems of low spectrum utilization and spectrum shortage [1, 2]. The key idea is that the secondary users (SUs) perform spectrum sensing and exploit the underutilized spectrum allocated for the licensed or primary users (PUs). When there exist multiple sensed free channels, orthogonal frequency division multiple access (OFDMA) can support highly efficient bandwidth utilization by allowing a SU to access these channels simultaneously. As such, the combination of OFDMA and CR has been an attractive technology in the future wireless communication system [3, 4].

Our work aims at designing and implementing a fully programmable cognitive radio system based on OFDMA. In the literature, there exist some previous works with the purpose of designing a practical platform for such a system [5-7]. However, these existing platforms are mainly based on programmable hardware such as field-programmable gate array (FPGA), embedded digital signal processors [6, 7], and even some application specific hardware [5]. One advantage of such platforms is that they can support real-time process of high-speed wireless protocols efficiently; however, developing on such platforms can be a difficult task, due to the hardware dependent programming language. Recently, a new software radio platform called Sora, designed by Microsoft Research Asia (MSRA), is able to address this challenge, thanks to its PC architecture [8]. In this letter, we present a novel cognitive radio system based on Sora platform, which provides high flexibility and full reconfigurability. The simulation results show that our system can perform robust communication in the cognitive environment.

2. Sora Platform

As a flexible software radio platform, Sora pushes as much communication functionality (e.g., baseband signal processing) as possible into software, and makes the hardware components simple enough to bridge the data transfer [8]. The overall system architecture is shown in Fig. 1, where the hardware consists of a high performance general computer, a radio control board (RCB), an RF-specific adaptor board (RAB), a radio board, and an antenna [9]. RCB is connected to the computer by high-speed PCI express (PCIe) interface, which can support high throughput communications and interact with the CPU cache through direct memory access (DMA) operation. The embedded FPGA on the RCB synchronizes the modulated frames and sends them to the radio board, in which the digital frames are converted into analog waves and sent to the receiver. The software driver kit (SDK) in Sora platform plays a role as a virtual network card in supporting IEEE 802.11a/b standards. Since the SDK implements the lower three layers of the OSI model, we can flexibly develop network applications and protocols without any dependence on the hardware.

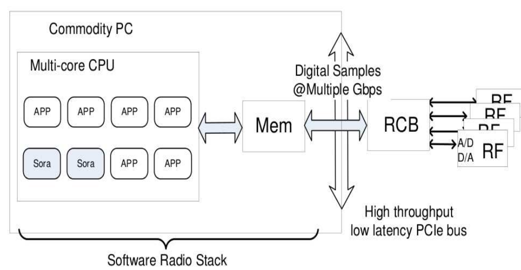


Fig.1. Sora system architecture

3. Sora-based CR System

In our established Sora-based CR system, there are three Sora platform-based nodes. The first one imitates the PU to communicate in the authorized spectrum, while the other two imitate the SUs which access the vacant spectrum without disrupting the transmission of the PU. The SUs should periodically sense the channels, indentifying the vacant spectrum and making a reasonable channel assessment before transmitting the data. By exploiting OFDMA as the multiple access scheme, different number of subcarriers can be adaptively combined into a subchannel assigned to the PU and SUs. The data packets are OFDM-modulated, which improves the robustness to a fast fading channel. The signal interaction of these three nodes is shown in Fig.2.

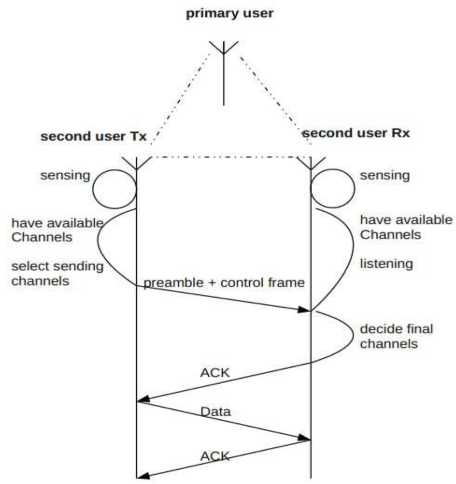


Fig.2. Signal interaction

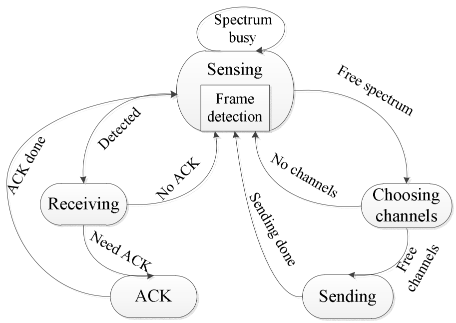


Fig.3. MAC state machine

The whole communication process is controlled and scheduled by the media access control (MAC) state machine shown in Fig. 3. Here, the event mechanism is utilized to wake up the sending and receiving threads. As the synchronization for the transmitter and the receiver is difficult to realize on the current Sora testbed, we set the transmitter as an active controller and set the receiver as a passive follower in the synchronization process. The SU transmitter keeps sensing until it finds free spectrum. Then it sets a timer and starts data transmission. When the timer expires, it restarts to sense. As a follower, the SU receiver gets synchronized by detecting the start of the sending frame from the SU transmitter. If it captures no frame, it will enter the sensing state as well. Otherwise, if it detects the coming frames, it starts to receive and demodulate the frames. The worker threads of the SU transmitter and receiver are omitted due to space limitation (interested readers can refer to [9]).

Spectrum sensing is a key function for a CR system. There are many detection methods for vacant frequency detection, such as coherent detection, cyclostationary detection, and energy detection, etc. For practical consideration, we choose energy detection since the SUs have no a priori knowledge about the PUs. The traditional energy detector cannot differentiate the interference and noise from the PU signal energy. As such, we choose the improved detector algorithm proposed in [10]. The termination threshold λ can be calculated using

$$\lambda = (\frac{\sqrt{2}Q^{-1}(P_{fa})}{\sqrt{N}} + 1)\sigma_0^2 \qquad (1)$$

where P_{fa} denotes the probability of false alarm, N denotes the number of the subcarriers, and σ_0^2 denotes the predicted noise energy. The derivation of σ_0^2 is according to the statistics of environment interference and noise. As a simple method, we set it as a fixed value after a period of estimation. Figs. 4 and 5 present respectively a snapshot of a spectrum occupation form of the PU got from a wireless spectrum analyzer and the sensing result. It can be observed that the sensing results match with the actual spectrum occupation. We also propose an iterative algorithm to estimate the noise energy as shown in (2), where β is the iteration step, θ denotes the compensation factor, x_i is the sample value, and λ_{n-1} is the last threshold. Fig. 6 shows the effectiveness of the proposed algorithm in terms of the iterative steps in noise energy estimation.

$$\sigma_n^2 = (1-\beta)\sigma_{n-1}^2 + \beta\theta E\{x_i^2 \mid x_i^2 < \lambda_{n-1}\} \qquad (2)$$

Table I shows the parameters and performance of our CR system. Figs.7 and 8 present respectively the spectrum image of the PU and SU sharing band and the demodulated constellation. These results reveal that our system efficiently utilizes the vacant spectrum and performs well as far as frame error rate (FER) is concerned.

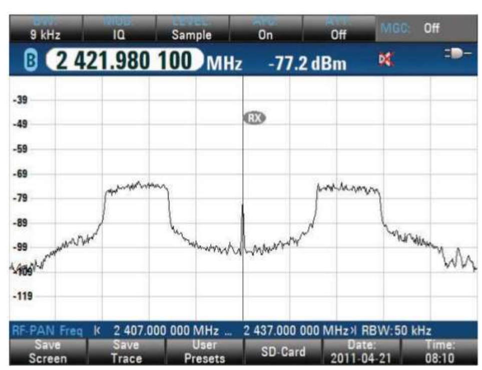


Fig.4. A snapshot of a spectrum occupation by the PU

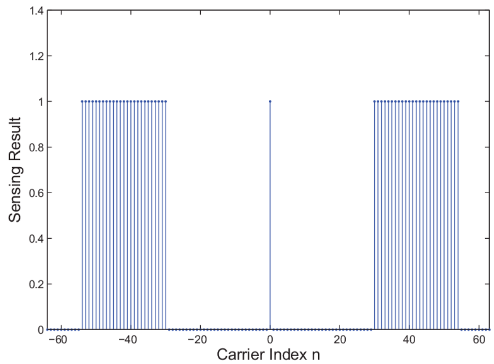


Fig.5. Spectrum sensing result

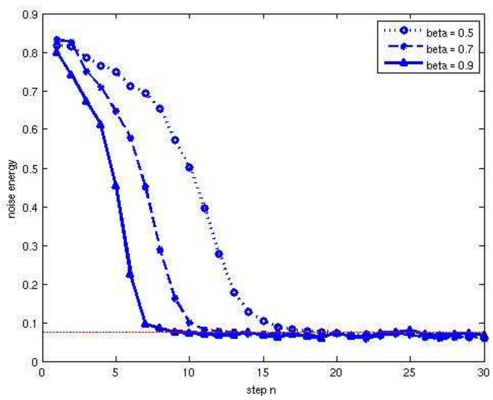


Fig.6. Performance of the iterative noise energy estimation algorithm

Table I. Parameters and performance

System parameters	Value
Center frequency	2.422GHz
Total bandwidth	20MHz
Carrier number	128
IFFT points	256
Prefix points	64
Symbol cycle	8μs
Maximum carrier number by SU	48
Data rate for SU with 16 QAM	12Mbit/s
FER for SU with 16QAM	10^{-3}

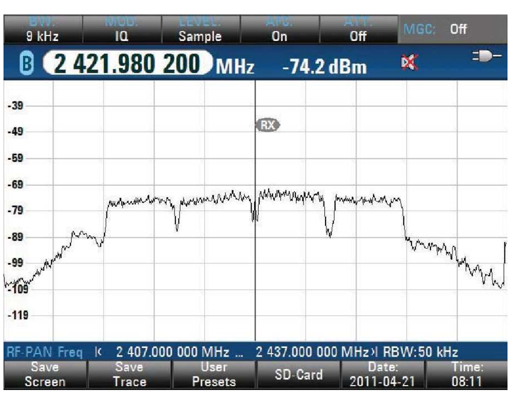


Fig.7. Spectrum shared by PU and SU

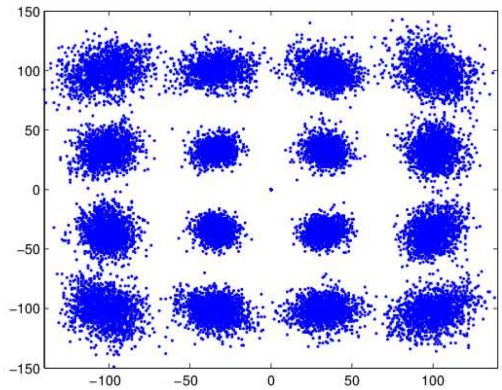


Fig.8. Constellation of demodulated data

4. Conclusions

In this letter, we present our cognitive OFDMA wireless communication system based on Sora, a fully programmable software radio platform. In our system, the cognitive users can efficiently sense the vacant spectrum and make an assessment and reasonable usage of the idle band to improve the frequency utilization. The test results show that our system support not only reliable sensing but also robust communication in the vacant spectrum.

Based on Sora, we can easily incorporate other functionality into our CR system. For instance, replacing the convolutional codes with rateless codes [11] can make the MAC state machine simpler, since no retransmission is required. Many other functions are under developing and testing.

References

[1] J. Mitola III and G. Q. Maguire, Jr., “Cognitive radio: Making software radios more personal,” *IEEE Pers. Commun.*, vol.6, no. 4, pp. 13-18, Aug. 1999.

[2] J. Mitola, “Cognitive Radio: An Integrated *Agent Architecture for Software Defined Raido*,” PhD thesis, Royal Institute of Technology, 2000.

[3] T. S. Rappaport, A. Annamalai, R. M. Buehrer, and W. H. Tranter, “Wireless communications: Past events and a future perspective,” *IEEE Commun. Mag.*, vol. 40, no. 5, pp. 148-161, May, 2002.

[4] IEEE Standard for local and metropolitan area networks Part 16: Air Interface for Broadband Wireless Access Systems, IEEE Standard 802.16, May 2009.

[5] Q. Zhang, G. J. M. Smit, L. T. Smit, A. Kokkeler, F. W. Hoeksema, and M. Heskamp, "A reconfigurable platform for cognitive radio," in Proc. *IEEE Mobile Technology, Application and Systems'*05, 2005

[6] S. Gupta, P. Murphy, C. Hunter, and A. Sabharwal, "Cognitive radio platforms: Wireless open-access research platform for networks," http://www-ece.rice.edu/~ashu/publications/cog-nitive.pdf

[7] A. Nafkha, C. Moy, P. Leray, R. Seguier, and J. Palicot, "Software defined radio platform for cognitive radio: design and hierarchical management," http://cdn.intechweb.org/pdfs/18325.pdf

[8] K. Tan, J. Zhang, J. Fang, H. Liu, Y.g Ye, S. Wang, Y. Zhang, H. Wu, W. Wang, and G. Voelker, "Sora: High performance software raido using general purpose multi-core processors," in *Proc. USENIX NSDI'09*, Apr. 2009, Boston, MA.

[9] L. Wang, Z. Zhang, L. Ye, B. Gong, and W. Lou, "Fully reconfigurable cognitive OFDMA testbed," in *Proc. IEEE Chiancom'11*, 2011.

[10] L. Ye, Z. Zhang, J. Zhang, and H. Zhang, "Carrier sending with self-cancelation of inter-carrier emission in cognitive OFDMA system," in *Proc. IEEE ICC'11*, 2011.

[11] D. J. C. MacKay, "Fountain codes," *IEE Proceedings Communication*, vol.152, no. 6, pp. 1062-1068, Dec. 2005.

Chuangmu Yao is a master student at Zhejiang University (ZJU). He obtained Bachelor degree in Communication Engineering in 2011 at ZJU. His research focuses on network coding, rateless coding, and software radio design.

Lianxiang Wang is a master student at Zhejiang University (ZJU). He obtained Bachelor degree in Communication Engineering in 2009 at ZJU. His research focuses on cognitive radio, software radio design.

Hangguan Shan received his B.Sc. and Ph.D. degrees respectively from Zhejiang University and Fudan University, in 2004 and 2009, all in electrical engineering. He was a postdoctoral research fellow in University of Waterloo from 2009 to 2010. In February 2011, he joined the Department of Information Science and Electronic Engineering, Zhejiang University, as an Assistant Professor. He is a co-recipient of the Best Industry Paper Award from IEEE Wireless Communications and Networking Conference (WCNC) 2011, Quintana-Roo, Mexico. His current research focuses on resource management and QoS provisioning in vehicular ad hoc networks, wireless body area networks, and cooperative networks. Dr. Shan has served on the Technical Program Committee (TPC) as member in IEEE VTC-Fall 2010, IEEE VTC-Fall 2011, IEEE iCOST 2011, IEEE IWCMC 2011, IEEE ICC 2011, IEEE ICC 2012, and IEEE IWCMC 2012.

Zhaoyang Zhang received his B.Sc. and Ph.D. degree from Zhejiang University in 1994 and

1998, respectively. He is currently a professor with the Institute of Information and Communication Engineering. Zhejiang University. He was selected into the Supporting Program for New Century Excellent Talents in University (NCET) by the Ministry of Education, China, in 2009. His research interests include multiuser information theory and advanced coding theory, distributed antenna systems, network signal processing, cooperative communications, and cognitive radio and cognitive radio networks. He has authored or co-authored more than 100 papers in the above areas. He is currently serving as Editorial Board Member and Associate Editor for the International Journal of Communication Systems and International Journal of Wireless Communications and Networking.

Playing Games in Cognitive Radio Networks

Danny Finn, Luiz DaSilva and Yong Xiao, Trinity College Dublin, Ireland
{finnda, dasilval, yongx}@tcd.ie

1. Introduction

Cognitive radio (CR) is a promising technology to solve inefficiencies in spectrum usage in the network generation of wireless systems. In CR networks, each mobile user has the ability to intelligently adjust its operating parameters according to its interactions with its surrounding environment. This makes *game theory* (a branch of social sciences which investigates interactions among autonomous decision makers) an ideal tool to solve the distributed optimization problems encountered by CR networks. One of the central concepts in game theory is the Nash equilibrium (NE) which is a balance point at which no decision maker can improve their payoff by unilaterally changing their strategy.

In this paper, we roughly classify the relationships between different users in CR networks into three types of interaction. The first is the interaction among opportunistic unlicensed spectrum users (i.e., mobile devices, service subscribers, etc.), called secondary users (SUs). The main focus of this interaction is to study how these unlicensed users can distributedly cooperate or compete with each other to exploit the limited spectrum resources. The second is interaction among the spectrum owners (i.e., telecommunication operators, spectrum regulators, etc.), called primary users (PUs). In this interaction, we study how these spectrum owners compete between one another through spectrum regulation and resource price adjustment to maximize their benefits by attracting the SUs to buy their services, while ensuring user quality of service within their own network. The third is the interaction between both SUs and PUs. In this interaction, we investigate the responses of the SUs (or PUs) to the changes in the strategies or states of the PUs (or SUs).

Different from most of the existing surveys [1] which only focus on the interaction among SUs, in this paper, we highlight recent game theoretic results on all three types of interactions in CR networks. We illustrate the relationships between the different CR interaction types and the games that we consider in Figure 2.

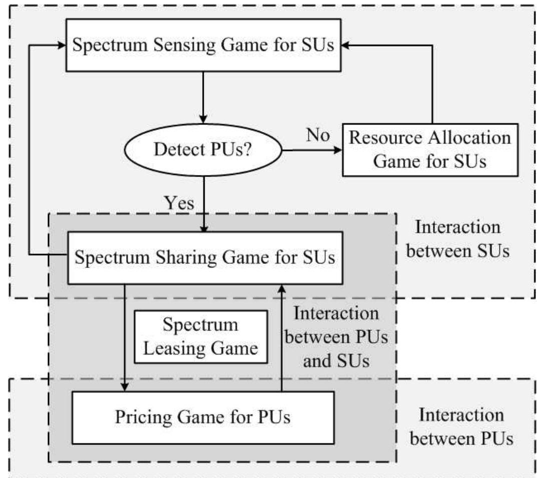


Figure 2: Games and CR interaction types

2. Interaction between SUs

Spectrum Sensing Game: In CR networks SUs are generally required to detect the presence of PUs in the licensed spectrum before deciding on a transmission strategy. It has been shown that allowing multiple SUs to sense the wireless medium cooperatively, called cooperative spectrum sensing, greatly improves the reliability and accuracy of detection. However, forcing all SUs to participate in the sensing process has been shown to be energy consuming and inefficient. How to choose the appropriate amount of SUs to sense is the main problem in spectrum sensing.

By formulating the spectrum sensing problem as a non-cooperative game, [2], [3] investigate the tradeoff between the sensing reliability and the incentive of the sensing SUs. More specifically, the authors in [2] formulate an evolutionary game-based framework to study the dynamic changing of the number of cooperative sensing SUs in large multi-user CR networks. By analyzing the behavior dynamics of the SUs, an evolutionarily stable strategy for the SUs is derived. The work in [3] studies the efficiency of the correlated equilibrium (CE), which can be regarded as a generalized version of the NE, in the spectrum sensing game. The CE is proven to provide better performance than the NE.

In practical CR networks, different SUs may have different neighboring PUs. In this case, studying how the SUs form different groups to collaboratively sense their common neighboring PUs is an important problem. Coalitional game theoretic methods have been proposed to tackle this problem. Distributed coalition formation and splitting methods for the cooperative spectrum sensing game are proposed in [4]. In [5] the authors study a more complicated scenario where each SU not only decides on a spectrum sensing group, but also chooses a subset of the primary channels, each of which are owned by one PU, to sense. It is shown that, when compared to a traditional scheme for fixed probability of false alarm and missed detection requirements, the application of the coalition formation game can significantly increase the number of channels available to the set of SUs and hence increase the spectrum efficiency of SUs.

Spectrum Sharing Game: Spectrum sharing games consider the situation where SUs and PUs are allowed to simultaneously transmit, at the same time, over the same frequency band, provided that the interference caused by the SUs to the PU network is below a certain tolerable level. One of the central problems of the spectrum sharing game is how to maximize secondary network throughput while ensuring the tolerable interference level of the PUs is not exceeded.

In [6] a non-cooperative repeated game-based framework is proposed to study the power control problem of the SUs. A distributed algorithm is proposed which approaches the time-averaged performance obtainable by choosing the NE in hindsight. Non-cooperative game methods are also considered for MIMO-based CR networks in [7] where the condition for which the NE is unique and globally asymptotic stabile is derived.

Resource Allocation Game:
Game theoretic methods are proposed to study sub-channel allocation problems in CR networks in [8], [9]. More specifically, [8] proposes a Q-learning-based distributed algorithm which is proven to converge to a NE of the sub-channel allocation game. [9] forms a cooperative game in which SUs negotiate sub-channel allocations according to Nash bargaining solution-based fairness criteria.

3. Interaction between PUs

Pricing game: By modeling PUs as spectrum sellers and SUs as spectrum buyers, game theory has been applied to study pricing competition, and cooperation, among PUs. In this game, each SU will only buy spectrum from the PU who offers the best price. Hence, how to choose an optimal pricing function to attract SUs that could provide the highest revenues is a very important problem for PUs.

Repeated games, as well as one shot games to address this problem are posed in [10], [11]. The former establishes a Bertrand game-based framework to study the effects of different system parameters on the performance of the Nash equilibrium, while the latter develops a game theoretic model using the game with incomplete information to study the pricing competition among PUs. [12] formulates the problem as a double spectrum auctioning problem. In [13], a coalitional game-based framework is proposed to study how PUs can cooperate with each other to decide on spectrum prices for SUs. It is proven that allowing all PUs (the grand coalition) to decide on the prices of all the frequency bands is generally not optimal. A distributed algorithm is proposed which incentivizes the partition of PUs into different groups for pricing decisions.

4. Interaction between both PUs and SUs

Spectrum Leasing Game: Game theory has also been shown to be an effective tool for analyzing the responses of PUs (or SUs) to the changes in strategy or actions of the SUs (or PUs). [14] studies the case where PUs adaptively impose caps on their maximum tolerable interference as a result of interaction with SUs in a non-cooperative game.

A Stackelberg game-based framework has been proposed in [15] to study the joint optimization of the prices of the PUs and the transmit powers and sub-bands of the SUs. It has proven that these three optimization problems are linked to one another through the pricing functions of the PUs. A distributed algorithm is proposed which converges to a unique Stackelberg equilibrium.

5. Conclusions

In this letter, we discuss recent game theoretic results for cognitive radio networks. We classify the game theoretic modeling of the CR network into three types of interaction, namely: interactions between SUs, interactions between PUs and interactions between both PUs and SUs.

References

[1] B. Wang, Y. Wu, and K. J. R. Liu, “Game theory for cognitive radio networks: An overview,” *Computer Networks*, vol. 54, no. 14, pp. 2537-2561, Oct. 2010.

[2] B. Wang, K. J. R. Liu, and T. C. Clancy, “Evolutionary cooperative spectrum sensing game: how to collaborate?,” *IEEE Transactions on Communications*, vol. 58, no. 3, pp. 890-900, Mar. 2010.

[3] S. Maharjan, Y. Zhang, C. Yuen, and S. Gjessing, “Distributed Spectrum Sensing in Cognitive Radio Networks with Fairness Consideration: Efficiency of Correlated Equilibrium,” in *IEEE MASS 2011, 17 - 22 Oct. 2011*.

[4] W. Saad, Z. Han, M. Debbah, A. Hjorungnes, and T. Basar, “Coalitional Games for Distributed Collaborative Spectrum Sensing in Cognitive Radio Networks,” in *IEEE INFOCOM 2009 - The 28th Conference on Computer Communications*, 2009, pp. 2114-2122.

[5] W. Wang, B. Kasiri, J. Cai, and A. S. Alfa, “Distributed Cooperative Multi-Channel Spectrum Sensing Based on Dynamic Coalitional Game,” in *2010 IEEE Global Telecommunications Conference GLOBECOM 2010*, 2010, pp. 1-5.

[6] Y. Xiao, G. Bi, and D. Niyato, “A Simple Distributed Power Control Algorithm for Cognitive Radio Networks,” *IEEE Transactions on Wireless Communications*, vol. 10, no. 11, pp. 3594-3600, Nov. 2011.

[7] G. Scutari and D. P. Palomar, “MIMO Cognitive Radio: A Game Theoretical Approach,” *IEEE Transactions on Signal Processing*, vol. 58, no. 2, pp. 761-780, Feb. 2010.

[8] H. Li, “Multi-agent Q-learning of channel selection in multi-user cognitive radio systems: A two by two case,” in *2009 IEEE International Conference on Systems, Man and Cybernetics*, 2009, pp. 1893-1898.

[9] Z. Han, Z. Ji, and K. J. R. Liu, “Fair Multiuser Channel Allocation for OFDMA Networks Using Nash Bargaining Solutions and Coalitions,” *IEEE Transactions on Communications*, vol. 53, no. 8, pp. 1366-1376, Aug. 2005.

[10] D. Niyato and E. Hossain, “Competitive Pricing for Spectrum Sharing in Cognitive Radio Networks: Dynamic Game, Inefficiency of Nash Equilibrium, and Collusion,” *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, pp. 192-202, Jan. 2008.

[11] G. S. Kasbekar and S. Sarkar, “Spectrum pricing games with bandwidth uncertainty and spatial reuse in cognitive radio networks,” in *Proceedings of the eleventh ACM international symposium on Mobile ad hoc networking and computing - MobiHoc ’10*, 2010, p. 251.

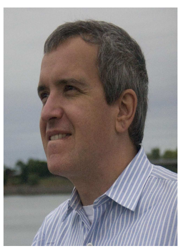
[12] X. Zhou and H. Zheng, “TRUST: A General Framework for Truthful Double Spectrum Auctions,” in *IEEE INFOCOM 2009 - The 28th Conference on Computer Communications*, 2009, pp. 999-1007.

[13] Y. Xiao and L. A. DaSilva, “Dynamic Pricing Coalitional Game for Cognitive Radio Networks,” in *IFIP networking 2012 Workshop HetNets, 25 May 2012*.

[14] S. K. Jayaweera, “Dynamic spectrum leasing in cognitive radio networks via primary-secondary user power control games,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 6, pp. 3300-3310, Jun. 2009.

[15] Y. Xiao, G. Bi, and D. Niyato, “Distributed optimization for cognitive radio networks using Stackelberg game,” in *2010 IEEE International Conference on Communication Systems*, 2010, pp. 77-81.

Danny Finn received B.A. (Mathematics) and B.A.I. (Engineering) degrees from Trinity College Dublin in 2010 where he is currently a Ph.D. candidate with CTVR / The Telecommunications Research Centre, Trinity College Dublin, Ireland. He is a key member of CREW - an FP7 project focusing on the creation of a federated test platform for advanced spectrum sensing and cognitive radio technologies. His research interests include cellular and cognitive radio network optimisation, and advanced physical layer adaptations.



Luiz DaSilva currently holds the Stokes Professorship in Telecommunications in the department of Electronic and Electrical Engineering at Trinity College Dublin, where he is a member of CTVR / The Telecommunications Research Centre in Ireland. He is also a Professor in the Bradley Department of Electrical and Computer Engineering at Virginia Tech, where he has been a faculty member since 1998. His research focuses on distributed and adaptive resource management in wireless networks, and in particular cognitive radio networks and the application of game theory to wireless networks. He is currently a principal investigator on research projects funded by the National Science Foundation, the Science Foundation Ireland, and the European Commission under Framework Programme 7. Prof. DaSilva has authored more than 100 refereed journal and conference papers and two books on wireless communications. He is a Senior Member of IEEE and in 2006 he was named a College of Engineering Faculty Fellow at Virginia Tech.

Yong Xiao received his B.S. degree in electrical engineering from China University of Geosciences, Wuhan, China in 2002, M.Sc. degree in telecommunication from Hong Kong University of Science and Technology in 2006, and his Ph.D degree in electrical and electronic engineering from Nanyang Technological University, Singapore in 2012. From August 2010 to April 2011, he was a research associate in school of electrical and electronic engineering, Nanyang Technological University, Singapore.

Currently, he is a Postdoctoral Researcher at CTVR / The Telecommunications Research Centre, Trinity College Dublin, Ireland. His research interests include information theory for cooperative communication systems, machine learning and application of game theory in multi-user wireless networks.

Applications and Opportunities for Cognitive Radio and Networks

Keith E. Nolan and Linda E. Doyle, Trinity College Dublin, Ireland
(keith.nolan@tcd.ie, ledoyle@tcd.ie)

1. Introduction

Over a decade has passed since the concept of cognitive radio (CR) was first developed. Now we are at the stage where the value of CR techniques in solutions for real-world communications problems is beginning to be realized. Spectrum sensing approaches have given way to the use of geo-location as part of CR for intelligent network management and coexistence between primary and secondary services [1]. In this paper, we present three aspects of cognitive radio and networks of importance to the research and commercial development community. We firstly outline key emerging application areas for CR/geo-location. Secondly, we look how the concept of whitespaces can be extended beyond the UHF band to other candidate spectrum segments. Thirdly, we examine regulatory policy changes being considered to increase spectrum efficiency and to support future demands for ubiquitous connectivity and capacity

2. Emerging CR Application Areas

We outline five key application areas for CR/geo-location techniques; data offloading for WiFi, machine communications, rural broadband, medical body area networks, and intelligent transportation systems.

2.1 WiFi & Data Offload

WiFi dominates the metropolitan area wireless network sector. It has become an important part of a mobile operators' strategy also through the use of data offloading. Data offloading involves migrating data traffic from cellular networks to metropolitan WiFi access points. This approach is being used by operators in an attempt to cope with surging mobile data demands that have doubled every year since 2009 [2]. However, the unmanaged license-exempt nature of the 2.4GHz ISM band presents a number of challenges that restricts the long-term suitability for data offloading. These challenges include an already highly-congested environment due to the almost ubiquitous deployment of WiFi access points, short range devices e.g. wireless headsets, baby monitors, home entertainment, and wireless security cameras. License-exempt whitespace spectrum for short range, high capacity data-offloading is set to be a primary application area for cognitive radio/geo-location technologies [3].

2.2 Machine to Machine (M2M)

M2M or more correctly, *machine communications*, describes device communications used for smart meter infrastructure, telematics, health monitoring, security, environmental sensor monitoring, and a wide variety of networks that operate independently of direct human interaction [4]. M2M is characterized by very low per-device data demands, extremely low duty cycles and power usage, and an operating lifetime measured in years using battery power for power-constrained applications. A smart meter reading for example involves just tens of bytes and may only need to be transmitted once per day. The future growth of M2M is measured in billions of devices and the target communications module cost is below $1 per device. The UHF band offers opportunities for wide area wireless M2M applications. Devices have already been deployed in Cambridge, UK. However, the low device cost and energy dissipation targets preclude the direct deployment of cognitive radio technologies within the device communications module itself. The potential for CR/geo-location technologies is at the basestation and core communications control levels. This creates opportunities for network adaptation, traffic analysis, and clever multi-solution management using CR techniques in a cloud-computing environment.

2.3 Rural Broadband

The challenge of providing reliable broadband internet coverage to wide regional areas and under-served and un-served rural communities around the world led to the use of UHF whitespaces due to the favorable long range and high-capacity characteristics. The need to protect incumbents and standardize the communications protocol resulted in the development and completion of the IEEE 802.22 standard [5]. Geo-location is an important part of the solution due to the cost and somewhat unreliable nature of spectrum sensing in wide-area rural network deployments. However, coordination between multiple different secondary user networks is not currently supported within this geo-location database framework. CR techniques and the deployment of spectrum sensing techniques at the basestation level can therefore play a significant role in the management of multiple secondary user networks in common geographical areas.

2.4 Medical Body Area Networks (MBANs)

Wireless medical sensors within the healthcare market are experiencing rapid growth in demand. In the US alone, the telecommunications services market for the healthcare sector is set to increase from over $7 billion in 2008 to in excess of $11 billion in 2013 according to a study by Insight Research Corporation. Medical body area networks (MBANs) improve the mobility of patients and medical personnel during surgery, accelerate the patients' recovery, and facilitate the remote monitoring of patients suffering from chronic diseases. Currently, MBANs are being used in license-exempt frequency bands, where the risk of interference with other communications devices tends to be high in medical care environments. Cognitive radio/geo-location techniques can potentially alleviate these problems in medical communication environments. In addition, these techniques can help increase the efficiency of spectrum usage to accommodate the rapidly-growing demand for wireless MBAN solutions and enhance coexistence with other collocated wireless systems [6].

2.5 Intelligent Transportation Systems

Energy efficiency improvements, carbon and cost reductions, and enhanced safety are three key drivers for intelligent transportation systems. New vehicle designs can feature a large range of different communications systems from cellular e.g. Long Term Evolution (LTE) and 3G, short range devices and sensors e.g. based on IEEE 802.15.4, and RFID/near-field communications, broadcast services (digital terrestrial television, satellite, and broadcast FM radio) and communications for power line carrier (PLC) in the case of electric vehicles. The plethora of communications and vehicular management systems in new vehicular designs creates a complex mobile data server. The value of CR is not to add to this complexity but in fact to automatically manage and reduce this. Key objectives include the need for technology to become a seamless part of the driver and occupants' experience, the potential for driver distraction is minimized, safety is maximized, and that updates and future enhancements can be incorporated remotely. CR opportunities for managing information, alert, and other ultra-low latency geo-messaging information from road signs, road works, and even other vehicles are viable business areas where this information can be incorporated into the vehicle systems for enhanced safety [7].

3. Extending Whitespaces

The TV whitespace concept has served as a catalyst for change in how we use and manage spectrum resources. Spectrum sharing and opportunistic usage can expanded across other frequency ranges. The band candidates include the L-band (1452MHz-1492MHz), 2.3GHz-2.4GHz International Mobile Telecommunication (IMT) band, and radar bands (2700MHz-3100MHz & 5250MHz-5850MHz).

In Europe, the L-band remains largely unused. In other areas, notably in North America, the take-up of DAB from terrestrial sources using the L-band has been very small, and the satellite services, while deployed, have small numbers of subscribers. Internet distribution of broadcast audio programming is now common (as it is also for broadcast video) and this has altered the commercial landscape for digital audio broadcast both terrestrial and via satellite. A number of countries have therefore been investigating the future use of the L-band. Industry Canada published a consultation document regarding the potential use of the L-band [10]. In Europe, the CEPT Electronic Communications Committee (ECC) launched a major review of the L-band with a view to making more effective use of this spectrum also. In the USA, a company called LightSquared aimed to provide a wholesale, nationwide 4G-LTE wireless broadband network integrated with satellite coverage across the country. However they faced technical concerns due to the potential for disruption to GPS devices [11.

Following the World Radio Congress (WRC) in 2015, a block of spectrum in the 694MHz-790MHz region is likely to be allocated for mobile service in ITU Region 1 [12]. This will create a likely commercial opportunity for the coexistence of CR/geo-location and cellular services necessitating more dynamic management due to the high degree of mobility involved compared to existing fixed-devices approach for current TVWS-based rural broadband.

4. New regulatory concepts and emerging standards

Authorized Shared Access (ASA)/Licensed

Shared Access (LSA) is an approach proposed by Qualcomm and Nokia [13]. This is a relatively new concept in spectrum management driven by the industry. The concept involves operators authorizing secondary usage of spare spectrum within their licensed bands but under tight controls to prevent any disruption to the primary user. The FCC is monitoring this development and CEPT is considering a further study on ASA. The RSPG acknowledged ASA in a recent consultation report stating that an ASA user can be granted a right to utilize under-used spectrum without interfering with the incumbent user. ASA spectrum would be licensed therefore it allows operators to maintain a predictable quality of service and to business cases for the build-out of mobile broadband network infrastructure where it is both economically and technically feasible.

Regarding standards, Weightless is an emerging proto-standard for M2M in TVWS being developed primarily by Neul based in Cambridge UK and a growing consortium of companies [14]. The IEEE 802.11af task group is focusing on wireless LAN in TVWS [15]. In the wireless personal area networks (WPAN) area, the IEEE 802.15.4m taskgroup is focusing on using TVWS [16]. This is a potential candidate standard for the MBAN application area outlined in Section 2.4. The IEEE 802.19.2 task group is focusing on wireless coexistence in TVWS [17] and IEEE 802.11ac essentially involves the use of CR without whitespaces in the 5GHz band for high throughput applications [18].

5. Summary

In this paper, we highlighted three key cognitive radio and network aspects; emerging application areas, opportunities for whitespace usage beyond the UHF band, and regulatory policy changes. Firstly, we highlighted WiFi and data offloading, machine communications, rural broadband, medical body area networks, and intelligent transportation systems as emerging CR/geo-location application areas. Secondly, we examined how the concept of whitespaces can be extended beyond the UHF band to other candidate spectrum segments. Thirdly, we outlined regulatory policy changes being considered to increase spectrum efficiency and to support future demands for ubiquitous connectivity and capacity.

Acknowledgments

This material is based upon works supported by Science Foundation Ireland under Grant No. 10/CE/I1853

References

[1] Pawelczak, P.; Nolan, K.; Doyle, L.; Ser Wah Oh; Cabric, D.; , "Cognitive radio: Ten years of experimentation and development," Communications Magazine, IEEE , vol.49, no.3, pp.90-100, March 2011

[2] Dimatteo, S.; Pan Hui; Bo Han; Li, V.O.K.; , "Cellular Traffic Offloading through WiFi Networks," Mobile Adhoc and Sensor Systems (MASS), 2011 IEEE 8th International Conference on , vol., no., pp.192-201, 17-22 Oct. 2011

[3] FP7 QUASAR, "The Commercial Sweetspot of Secondary Spectrum", EC Workshop on Flexible Spectrum Usage (FlexSUS), Brussels, Feb 13, 2012 url: http://zandercom.com/wordpress/wp-content/uploads/FlexSUS20120213.pdf

[4] Analysys Mason article "Imagine an M2M world with 2.1 billion connected things …", January, 2011.url: http://www.analysysmason.com/about-us/news/insight/M2M_forecast_Jan2011/

[5] "IEEE Standard for Information Technology--Telecommunications and information exchange between systems Wireless Regional Area Networks (WRAN)--Specific requirements Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands," IEEE Std 802.22-2011 , vol., no., pp.1-680, July 1 2011

[6] Jianfeng Wang; Ghosh, M.; Challapali, K.; , "Emerging cognitive radio applications: A survey," Communications Magazine, IEEE , vol.49, no.3, pp.74-81, March 2011

[7] Niyato, D.; Hossain, E.; Ping Wang; , "Optimal Channel Access Management with QoS Support for Cognitive Vehicular Networks," Mobile Computing, IEEE Transactions on , vol.10, no.4, pp.573-591, April 2011

[8] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2010–2015, September, 2011. url:http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html

[9] Plum Consulting, "Economic study of the benefits from use of 1.4 GHz for a supplemental mobile downlink", June 2011.url: http://www.slideshare.net/zahidtg/plum-june2011-benefitsof14ghzspectrumformultimediaservices

[10] Industry Canada, Consultation on the Spectrum Allocations and Spectrum Utilization Policies for the Frequency Range 1435-1525 MHz (L-Band), url: http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf09751.html

[11] GPS.gov, LightSquared and GPS, url: http://www.gps.gov/spectrum/lightsquared/

[12] Rajesh Mehrotra, Redbrooks Consultants Inc.,"Results of WRC-12 and Regulatory Implications on Spectrum Management" url: http://www.itu.int/ITU-D/asp/CMS/Events/2012/ITP2012/Rajesh_Mehrotra_WRC-12.pdf

[13] RSPG Consultation on Cognitive Technologies, Qualcomm And Nokia Corporation Joint Response, January 2011. url: http://rspg.groups.eu.int/consultations/consultation_cognitiv_2010/ qualcomm_nokia_0114.pdf

[14] Weightless consortium, http://www.weightless.org

[15] IEEE 802.11af, Wireless LAN in the TV White Space, url: http://grouper.ieee.org/groups/802/11/Reports/tgaf_update.htm

[16] IEEE 802.15 Task Group 4M, url: http://www.ieee802.org/15/pub/TG4m.html

[17] IEEE 802.19 Task Group 1, Wireless Coexistence in the TV White Space, url: http://ieee802.org/19/pub/TG1.html

[18] IEEE P802.11 Task Group AC, url: http://www.ieee802.org/11/Reports/tgac_update.htm

Author Information

Linda DOYLE a Professor in Trinity College, University of Dublin, Ireland in the School of Engineering. Professor Doyle is the Director of CTVR. CTVR is a national research centre focusing on industry-informed research in the telecommunications field. CTVR is headquartered in Trinity College and based in six other Irish academic institutions with over 80 active researchers. Prof Doyle's own area of research is in wireless communications with a particular focus on cognitive radio, reconfigurable networks, spectrum management and art & technology. Her group has built an international reputation in experimental cognitive radio work. She wrote a book on The Essentials of Cognitive Radio, and published by Cambridge University Press. Prof. Doyle has also played a role in spectrum policy at a national level and has been involved with the Irish Department of Communications in writing a white paper on spectrum policy for Ireland.

Keith NOLAN is a Research Fellow in Trinity College Dublin in the Department of Electronic & Electrical Engineering and currently with the Telecommunications Research Centre (CTVR).
Dr. Nolan received his Ph.D. in Electronic Engineering in 2005, which focused on reconfigurable orthogonal frequency division multiplexing (OFDM) systems. Within CTVR at TCD, he is leading a number of industry-focused commercialization projects based on M2M communications, CR & SDR, and DSA systems. Dr. Nolan chairs a working group on economic aspects of CR/SDR regulation within a European collaborative project called COST-TERRA. He also acts as a liaison officer between the Wireless Innovation Forum (WInnF) and COST-TERRA & COST-IC0902.

MMTC Officers

CHAIR

Jianwei Huang
The Chinese University of Hong Kong
China

STEERING COMMITTEE CHAIR

Pascal Frossard
EPFL, Switzerland

VICE CHAIRS

Kai Yang
Bell Labs, Alcatel-Lucent
USA

Chonggang Wang
InterDigital Communications
USA

Yonggang Wen
Nanyang Technological University
Singapore

Luigi Atzori
University of Cagliari
Italy

SECRETARY

Liang Zhou
Nanjing University of Posts and Telecommunications
China