



## TCCN Newsletter

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### CONTENTS

|  |    |
|--|----|
| <i>Director's Message</i> .....  | 2  |
| <i>Editorial of TCCN Newsletter</i> .....  | 3  |
| <i>Editor: Lingjie Duan (LD), Singapore University of Technology and Design</i> .....                                | 3  |
| <i>An Interview with Dr. Jeffrey Andrews on mmWave Spectrum Sharing</i> .....  | 5  |
| <i>An Interview with Dr. Randall Berry on Spectrum Sharing's Economic Impact</i> .....                               | 7  |
| <i>An Interview with Dr. Thomas Hou on Optimizing CR Performance for Multi-hop Ad Hoc Networks</i> .....             | 9  |
| <i>An Interview with Dr. Cheng-Shang Chang on Multichannel Rendezvous Problems in Cognitive Radio Networks</i> ..... | 11 |
| <i>An Interview with Dr. Zhu Han on Cognitive Radio VANETs</i> .....   | 13 |
| <i>An Interview with Dr. Mihaela van der Schaar on Multi-agent Learning and Decision Making</i> .....                | 15 |
| <i>An Interview with Dr. Narayan Mandayam on Prospect Pricing in CRNs</i> .....                                      | 17 |
| <i>An Interview with Dr. K.P. (Suba) Subbalakshmi on Cognitive Cloud Offloading</i> .....                            | 19 |
| <i>An Interview with Dr. Ranveer Chandra on TV White Space Networks</i> .....  | 21 |
| <i>TCCN Newsletter Editorial Board</i> .....   | 23 |
| <i>TCCN Officers</i> .....   | 23 |

# IEEE COMSOC TCCN Newsletter

## Director's Message

Dear Fellow TCCN Members,

I am very happy to introduce to you the second issue of *TCCN Newsletter* (previously called *TCCN Communications*). I would like to express my sincere thanks to TCCN Chair, Prof. Ying-Chang Liang, and other TCCN officers for their enthusiastic support for this initiative to serve the community.

*TCCN Newsletter* is an electronic platform dedicated to excel in the following aspects:

- Introducing forward-looking research ideas,
- Updating members on new industry, standard, and policy initiatives,
- Promoting top-quality publications with high potential impacts,
- Increasing the visibility of TCCN within ComSoc and beyond.

In this issue, we introduce a new series of “virtual interviews”, with some of the influential researchers in the TCCN community. We asked each interviewee to share with TCCN members regarding his/her most significant recent work in cognitive networks, the most unique and impressive aspects of the work, the challenges and lessons encountered during the research, and the plans for the next few years.

I would like to thank Prof. Lingjie Duan from Singapore University of Technology and Design, who serves as the editor of this virtual interviews series. After sending out the interview invitations early 2016, we have received enthusiastic responses from the community. The interview results published in this issue only represent a subset of interviews that we have been working on. In the future, we will regularly publish virtual interviews with researchers of diverse research and geographical backgrounds.

As always, I would like to welcome any suggestions from TCCN members regarding how to make TCCN Newsletter more interesting and informative to the community. Please feel free to contact me at [jwhuang@ie.cuhk.edu.hk](mailto:jwhuang@ie.cuhk.edu.hk) if you have any suggestions.

Thanks and best regards,



Jianwei Huang

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## Editorial of TCCN Newsletter

*Editor: Lingjie Duan (LD)*

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Future wireless networks are expected to be highly cognitive and smart by efficiently harvesting and utilizing limited resources for communications. An engineering system way of thinking is required to innovate in technological, economic, and policy aspects. In the past three years, we observe new challenges and opportunities in the advancement of this cognitive networking area, which motivates us to interview some influential researchers to report their most interesting recent works to the TCCN community readers.

This series of virtual interviews brings together eight top researchers to touch upon the new research challenges and opportunities brought forward by cognitive networking, and summarize their different contributions, experiences, and future research directions.

The first interview with Jeffrey Andrews introduces his work on analyzing the feasibility of spectrum license sharing in mmWave systems, which attract many attentions from industry recently. His work provides a new theoretical framework to analyze spectrum sharing in multi-operator mmWave systems, and analytically investigates the usefulness and the right amount of inter-operator coordination for certain QoS requirement. The second interview with Randall Berry looks at an economic perspective and introduces how different approaches of spectrum sharing affect the economic incentives of wireless operators (e.g., in market competition and network investment).

Next, the third interview with Thomas Hou introduces his work on optimizing performance of cognitive radios for multi-hop ad hoc networks, by exploring the advances at the PHY layer in practice. The fourth interview with Cheng-Shang Chang introduces the rigorously defined multichannel rendezvous problem to minimize time-to-rendezvous of secondary users in cognitive radio network, by theoretically deriving the fundamental limit.

The fifth interview with Zhu Han covers his recent work to extend cognitive radio networking to vehicular networks for better spectrum utilization, where new graph coalitional game is

proposed for distributed resource allocation. The sixth interview with Mihaela van der Schaar introduces the new methods of multi-agent learning and decision making to enable intelligent data use for learning and user interaction in cognitive networks. The seventh interview with Narayan Mandayam introduces the new models of end-user behavior in cognitive radio networks (CRNs) and the impact on resource allocation and dynamic pricing.

Finally, the eighth interview with K.P. Subbalakshmi introduces the confluence of mobile computing and cognitive network advances to develop a new approach called Cognitive Cloud Offloading. It uses bandwidth aggregation and multi-RAT technologies to efficiently manage computational and other resource demands on mobile devices. The last interview with Ranveer Chandra introduces his work on the realization of TV White Space networks in different parts of the world, by overcoming the interference problem with TV signals and adapting to the requirements of each country.

It would be a challenging job to paint a complete picture of the cognitive networking research through eight interviews. Still, we hope this series of virtual interviews gather together interesting state-of-the-art contributions that touch upon various aspects of cognitive networking, and promotes insightful future research directions.

Our special thanks go to all interviewees for contributing their significant research works to this series of interviews and sharing with us their useful experiences and future heading. I would like to acknowledge the gracious support from the Newsletter Director Jianwei Huang and all TCCN officers.

## IEEE COMSOC TCCN Newsletter



**Lingjie Duan** (S'09-M'12) received the Ph.D. degree from The Chinese University of Hong Kong in 2012. He is an Assistant Professor with the Singapore University of Technology and Design (SUTD). His research interests include network economics and game theory, cognitive communications and cooperative networking, and energy harvesting wireless communications. He is an Editor of IEEE Communications Surveys and Tutorials. He currently serves as a Guest Editor of the IEEE Journal on Selected Areas in Communications by co-leading a new

special “Human-in-the-loop mobile networks”, and also serves a Guest Editor of the IEEE Wireless Communications Magazine for feature topic “Sustainable green networking and computing for 5G systems”. He is a TPC member of numerous top conferences in communications and networking (e.g., IEEE INFOCOM, WiOPT, and SECON, and ACM MobiHoc). He received the 10th IEEE ComSoc Asia-Pacific Outstanding Young Researcher Award in 2015, the Hong Kong Young Scientist Award (Finalist in Engineering Science track) in 2014.

**An Interview with Dr. Jeffrey Andrews on mmWave Spectrum Sharing**

1) Could you briefly introduce one interesting work contributed by you in past three years? - LD

(JA) For your audience, I think our recent work on analyzing the feasibility of spectrum license sharing in mmWave systems would be of interest. We've gotten a lot of interest in this work from industry, especially operators and also regulatory agencies have been citing it. This is joint work with Robert Heath and our student Abhishek Gupta. MmWave, which for our purposes here, can be as low as about 15 GHz carrier frequency, is intriguing for making cognitive type radios and spectrum sharing more feasible. This is due to directionality of transmission and susceptibility to blocking: both of which make closing the link hard but also greatly reduce the impact of interference. For this reason, conventional licenses, which give each cellular operator complete and exclusive license over a band of spectrum, seems wasteful for mmWave systems. Thus, we investigate if sharing of spectrum licenses is more beneficial than exclusive licensing. We also address the extent of coordination required among operators to make this sharing practical.

2) What would you say is the most unique and impressive aspect of this work and why? - LD

(JA) There exists past work that evaluate spectrum sharing via simulations. This work establishes a theoretical framework to analyze spectrum sharing in multi-operator mmWave systems. An analytic framework relying on stochastic geometry helps us derive tractable expressions for the system performance and extract clear insights regarding various factors impacting the feasibility of spectrum sharing. As opposed to simulations, our results are totally transparent.

3) Is there any main insight or take-away from this work? – LD

(JA) The main take-away is that cellular mmWave operators can simply share their spectrum licenses without any explicit coordination and still achieve higher rates when compared to the rate achieved when exclusive licensing given that their beams are sufficiently

narrow, for example about 30 degrees, which is not even that narrow for a mmWave system. This result is of interest as well to agencies like the FCC and OfCom, who are trying to figure out how to auction off or otherwise deploy this spectrum, and intuitively feel that the same old exclusive license paradigm used for 1 and 2 GHz systems does not make sense at mmWaves.

4) Could you tell us some of the implications of this result for the real world? -LD

(JA) Well, clearly operators can improve the data rates they provide and also reduce their licensing costs, by sharing. For example, in the USA, AT&T and Verizon could split the cost of a license and still provide high data rates to nearly all their users, with basically no coordination at all. Coordination or sensing could help further, of course. But as seen in past, coordination is a challenge.

5) Where will be your future research heading in the next two years? –LD

(JA) We want to better understand the role of inter-operator coordination in sharing spectrum licenses. Coordination is generally not needed for mmWave systems from a median user perspective, but intelligent coordination can improve the performance of cell edge users or those otherwise with bad interference conditions. Since a high level of coordination will increase feedback overhead, there is a need to find just the right amount of coordination required. Another example where coordination can help is the secondary licensing scenario where an operator lets secondary operators transmit in its band. Here, coordination may be needed to guarantee certain QoS for the original operator.

6) Could you provide our readers link to your papers related to this work? -LD

(JA) Interested readers can access our work at arXiv.org for the time being.

The main work discussed in this interview is this one:

A. Gupta, J. G. Andrews, and R. W. Heath, "On the Feasibility of Sharing Spectrum Licenses in mmWave Cellular Systems", under revision,

## IEEE COMSOC TCCN Newsletter

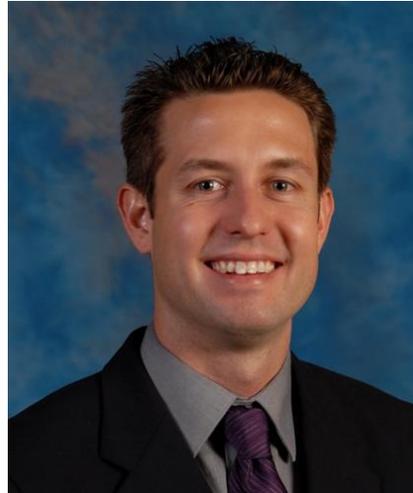
*IEEE Trans. on Communications*, available at <https://arxiv.org/abs/1512.01290>

We also recently developed another paper which analyzes a secondary licensing scheme, where secondary operators have to restrict their transmit power to limit their interference to the original operators:

A. K. Gupta, A. Alkhateeb, J. G. Andrews, and R. W. Heath Jr, "Gains of restricted secondary licensing in millimeter wave cellular systems," submitted to *IEEE Journal on Sel. Areas in Communications*, May 2016, available at <https://arxiv.org/abs/1605.00205>

Finally, for comprehensive tutorial treatment on mmWave cellular systems and their analysis, we'd also like to point out this recent work:

J. G. Andrews, T. Bai, M. Kulkarni, A. Alkhateeb, A. Gupta, and R. W. Heath, "Modeling and Analyzing Millimeter Wave Cellular Systems", invited paper, under review at *IEEE Trans. on Communications*, May 2016, available at <https://arxiv.org/abs/1605.04283>



**Jeffrey Andrews** (S'98, M'02, SM'06, F'13) received the B.S. in Engineering with High Distinction from Harvey Mudd College, and the M.S. and Ph.D. in Electrical Engineering from Stanford University. He is the Cullen Trust Endowed Professor (#1) of ECE at the University of Texas at Austin and the Editor-in-Chief of the *IEEE Transactions on Wireless Communications*. He developed Code Division Multiple Access systems at Qualcomm from 1995-97, and has consulted for entities including Apple, Samsung, Verizon, AT&T, the WiMAX Forum, Intel, Microsoft, Clearwire, Sprint, and NASA. He is a member of the Technical Advisory Board of Fastback Networks, and co-author of the books *Fundamentals of WiMAX* (Prentice-Hall, 2007) and *Fundamentals of LTE* (Prentice-Hall, 2010).

Dr. Andrews is an ISI Highly Cited Researcher, received the National Science Foundation CAREER award in 2007 and has been co-author of fourteen best paper award recipients including the 2016 IEEE Communications Society & Information Theory Society Joint Paper Award, the 2011 and 2016 IEEE Heinrich Hertz Prize, the 2014 IEEE Stephen O. Rice Prize, and the 2014 IEEE Leonard G. Abraham Prize. He received the 2015 Terman Award, is an IEEE Fellow, and is an elected member of the Board of Governors of the IEEE Information Theory Society.

**An Interview with Dr. Randall Berry on Spectrum Sharing's Economic Impact**

1) Could you briefly introduce the most significant work that you have contributed to the cognitive networks research in the past three years? - LD

(RB) A main motivation of cognitive networks is to enable greater sharing of spectrum and in doing so improve the services provided to end-users. In most cases wireless service providers provide these services. The main focus of much of my group's recent work related to cognitive networks has been on studying how different approaches to spectrum sharing impact the incentives of wireless service providers to compete for customers and invest in their networks. For example, if a secondary service provider shares a band of spectrum with a primary, then how would the primary react in terms of how it prices its service? Would it invest less in its network compared to the case where the spectrum was not shared?

2) What would you say is the most unique and impressive aspect of this work? - LD

(RB) I think some of the more interesting things coming out of this work are that we are able to show that the desired goals of new spectrum sharing approaches may not arise due to the economic incentives of service providers. The first such result we had in this area was in a paper with Michael Honig, Thanh Nguyen, Rakesh Vohra, and Hang Zhou, which showed that in some cases adding additional open access spectrum to an existing market could lead to the overall economic welfare declining instead of improving as one would hope. The issue here is that this new spectrum can be used to compete against incumbent providers, who in some cases have an incentive to raise prices, driving traffic to the new unlicensed band and congesting it.

3) How did you come to those findings? - LD

(RB) I have been fortunate enough to work with a great group of collaborators that includes both economists as well as wireless networking researchers as well as a great group of PhD students at Northwestern. This collaboration has been a great help in developing the models we have been studying.

Another factor is paying attention to current policy trends and attending workshops in which researchers from the policy community are present. In many cases, the technical and policy communities are looking at issues from very different perspectives. Combining these two views can be helpful in formulating new and interesting questions.

4) What were the main challenges that you had to overcome? -LD

(RB) In any multidisciplinary research like this, a key challenge is learning to speak the same language as your collaborators. I think an even greater challenge is to understand the "value system" of each discipline. By this I mean understanding how different fields value what questions and results are important.

5) How does that have implications for the real world? -LD

(RB) I think one of the main implications of our work for the real world is in providing "cautionary tales" to highlight possible unintended consequences of different spectrum sharing policies. Hopefully, one can gain insights from this into how policy can be crafted to ensure that new spectrum sharing technology leads to the desired outcome in the market place.

6) Would you please describe the lessons you learned to help the reader avoid pitfalls in his own work? -LD

(RB) It is often said that "asking the right questions" is an important part of doing research. I think this is something that bears repeating and is even truer in multidisciplinary settings. It can be tempting to rush this process – indeed one can easily find example of "multi-disciplinary" work where researchers in one field borrow an approach from another without taking the time to really understand if applying this approach is really answering the right question in their field. The main lesson I want to share is to take time understanding different perspectives and be willing to change directions if a given approach turns out not to be the best.

## IEEE COMSOC TCCN Newsletter

7) Where will be your future research heading in the next two years? Would you please provide a few references in this direction? -LD

(RB) I think there are still many interesting questions related to spectrum sharing and feel that activity is really starting to pick up in this area for example with the new rules being established for the 3.5 GHz band and for mm-wave, as well as the industry interest in 5G and IoT. We are looking at some new questions motivated by these areas. Some other interesting things are considering sharing infrastructure in addition to spectrum (which 5G architectures may help facilitate) and thinking about how to use spectrum measurements and other forms of data from a market perspective.



**Randall A. Berry** received his PhD in Electrical Engineering and Computer Science from the Massachusetts Institute of Technology in 2000 and subsequently joined Northwestern University where he is currently a Professor of Electrical Engineering and Computer Science. Dr. Berry is a IEEE Fellow, a recipient of a NSF CAREER award, and was an IEEE Communications Society Distinguished Lecturer for 2013-14. He has served as Editor for the *IEEE Transactions on Wireless Communication*, the *IEEE Transactions on Information Theory* and a guest editor for the *IEEE Journal on Selected Topics in Signal Processing* and the *IEEE Journal on Selected Areas in Communication*.

**An Interview with Dr. Thomas Hou on Optimizing CR Performance for Multi-hop Ad Hoc Networks**

1) When did you start your research on cognitive radio networks and what brought you to this field? -LD

(TH) I started my research on cognitive radio networks about 12 years ago when the subject was still new to the networking research community. It was through a number of conversations with my colleague at Virginia Tech, Jeff Reed that I began to realize the potential of cognitive radio on wireless networking. At that time, people working on software-defined radio and cognitive radio were mainly from the signal processing and radio communities. My group was one of the first to extend this research to the networking community. Also, at that time, the biggest customer for the SDR and CR technologies were US DoD, or JTRS program in particular. Since a tactical SDR would be mainly used in a mobile ad hoc network setting, we focused our research on optimizing performance of SDR/CR for multi-hop ad hoc networks.

2) Could you briefly describe some of the most significant contributions that you have made to the cognitive networks research community? -LD

(TH) Our group at Virginia Tech has made a number of contributions that have been recognized by the community. First and foremost, back 12 years ago, when SDR research was limited to the signal processing community, there was a lack of tractable analytical models of SDR/CR for networking research. One of the core challenges was that such models require interaction of algorithms/mechanisms across multiple layers, such as signal design at the physical (PHY) layer, scheduling at the link layer, and routing at the network layers. Our group did substantial work in this area by introducing new tractable cross-layer models for SDR/CR that have been widely cited and used in the community. Such cross-layer mathematical modeling work is still significant as new PHY layer technologies emerge and new interference management techniques become available.

Another contribution we made to the community is the development of mathematical tools to solve complex cross-layer optimization

problems. As you know, efficient spectrum sharing typically can be mapped into some kind of global optimization problems, involving variables from multiple layers distributed among the nodes in the network. Such optimization problems are notoriously hard to solve and it is necessary to develop some innovative solutions. We did a lot of work in this area and have published a book titled *Applied Optimization Methods for Wireless Networks* (Cambridge University Press, 2014) that summarized some useful techniques to solve complex cross-layer optimization problems.

3) What would you say is the most unique and impressive aspect of this work? -LD

(TH) A central theme of my research is to explore new performance envelope for CR networks by exploiting advances at the PHY layer. Unlike wired networks, where the underlying PHY layer can be considered as a bit pipe and thus be decoupled when studying networking problems, the performance of CR networks, or wireless networks in general, hinges upon the underlying PHY layer technologies. Any advancement or revolution at the PHY layer may bring a fundamental change or even a paradigm shift in upper layer network performance. Some examples include MIMO, full duplex, interference alignment, and mmWave communications, among others. Therefore, new performance envelopes need to be found for wireless networks under these new PHY layer technologies.

4) What were the main challenges that you had to overcome? -LD

(TH) The biggest challenge that we experienced during our development of tractable models for new PHY layer technologies is to prove whether such new models are indeed feasible in reality. This is a fundamental and important question, but somehow overlooked by some researchers. For example, when we were studying MIMO degree-of-freedom (DoF) based interference cancellation (IC) model, we reminded ourselves constantly that any IC scheme must be feasible for implementation at the PHY-layer (i.e., the existence of feasible precoding and decoding vectors). As a result, a DoF-based IC scheme

## IEEE COMSOC TCCN Newsletter

cannot be used arbitrarily at any transmit or receive node, but must follow certain rules to ensure PHY-layer feasibility. This important observation was unfortunately overlooked by some networking researchers and it turned out that their IC schemes were not feasible. Recognizing this important issue, we have been constantly reminding ourselves to prove PHY-layer feasibility when developing new models. Such proofs are typically based on construction and can be very challenging sometimes.

5) What do you consider the most significant research opportunities of our time? –LD

(TH) There are many research opportunities. But one area that fascinates me is how interference management is evolving in recent years. The classic approach for interference management is based on avoidance (e.g., CSMA or TDMA/FDMA/CDMA). But this approach is considered inefficient nowadays as simultaneous transmissions in the same airwave are becoming common thanks to new PHY-layer techniques that can mitigate interference and decode the desired signals. This new direction has fundamentally changed traditional approach to design scheduling or multiple access schemes for wireless networks. If you consider multi-hop network environment, the problems become even more interesting and challenging. There is enormous space for research out there.

6) What are your current major research projects? –LD

(TH) We have just got a new project from the US National Science Foundation's Enhancing Access to the Radio Spectrum (EARS) program. The goal of the project is to address the coexistence grand challenge in the real world by tackling two of the most popular wireless services (Wi-Fi and cellular) on the unlicensed radio bands as well as radar bands. Our research on coexistence between Wi-Fi and cellular takes a new approach to resolve the potential conflict between the two technologies by shifting focus to the user side and maximizing total user satisfaction. Our research on coexistence between radar and cellular on the radar bands explores the largely untapped radar spectrum that the government is considering for coexistence. Also, tightly integrated with our project are our planned efforts to study and improve spectrum

policies. Unlike other wireless research which is only loosely tied to policies and regulations, efficient spectrum sharing and coexistence of cross-technologies are all policy-driven. A keen understanding of current FCC regulations and pro-active interactions with government regulatory bodies are crucial to realize the potential of new coexistence technologies.



**Thomas Hou** is the Bradley Distinguished Professor of Electrical and Computer Engineering at Virginia Tech, USA. He has been working in the area of cognitive radio networks for over 12 years. His research interests are to develop innovative solutions to complex cross-layer optimization problems. He is particularly interested in exploring new limits of network performance by exploiting advances at the physical layer. Prof. Hou was named an IEEE Fellow for contributions to modeling and optimization of wireless networks. He has published two textbooks: *Cognitive Radio Communications and Networks: Principles and Practices* (Academic Press/Elsevier, 2009) and *Applied Optimization Methods for Wireless Networks* (Cambridge University Press, 2014). The first book was selected as one of the Best Readings on Cognitive Radio by the IEEE Communications Society. Prof. Hou is a member of IEEE Communications Society Board of Governors and the Chair of IEEE INFOCOM Steering Committee.

**An Interview with Dr. Cheng-Shang Chang on Multichannel Rendezvous Problems in Cognitive Radio Networks**

1) Could you briefly introduce the most significant work that you have contributed to the cognitive networks research in the past three years? - LD

My colleagues and I were particularly interested in the multichannel rendezvous problem in cognitive radio networks in the past three years. In such a problem, there are two secondary users who would like to rendezvous on a common unblocked channel. The objective is to minimize the time-to-rendezvous (TTR). The main contribution of our work is to derive the fundamental limits (lower bounds) for TTR under various channel assumptions/settings. This work, titled "Tight lower bounds for channel hopping schemes in cognitive radio networks," is going to appear in *IEEE/ACM Transactions on Networking*. This work is coauthored with Prof. Wanjiun Liao, National Taiwan University, and her PhD student, Mr. Tsung-Ying Wu.

2) What would you say is the most unique and impressive aspect of this work? - LD

For the multichannel rendezvous problem, most works in the literature focused on proposing channel hopping algorithms and analyzing their achievable performance. However, it is not clear whether these algorithms are optimal and how far they are away from the optimal ones. With our lower bounds, we were able to close the gaps under certain channel assumptions. As such, some existing algorithms are indeed optimal under certain channel assumptions and they cannot be improved further. In some cases, we also developed new channel hopping algorithms that are either optimal or have the TTRs much closer to the limits than the existing algorithms.

3) How did you come to those groundbreaking findings? - LD

In my view, the multichannel rendezvous problem was not defined rigorously before. With a rigorous mathematical formulation, we can look into this problem with the knowledge we have learned from early works in the area of rendezvous search. In particular, we applied

several well-known mathematical tools to the multichannel rendezvous problem, including finite projective planes, orthogonal Latin squares, and cyclic difference sets.

4) What were the main challenges that you had to overcome? -LD

The multichannel rendezvous problem is different from the classical rendezvous search problem in the sense of *load balancing*. For such a problem, we would like to have the two secondary users to rendezvous on all the available channels as *evenly* as possible. The load constraint adds a new dimension to the rendezvous search problem and that requires a new treatment for the lower bounds on the TTRs.

5) How does that have implications for the real world? -LD

The multichannel rendezvous problem (with a load constraint) is a new class of rendezvous search problems and we believe it will have many real-world applications, including cognitive radio networks. The fundamental limits that we derived show us where the state-of-the-art channel hopping algorithms stand and how much room we can improve from there.

6) Would you please describe the lessons you learned to help the reader avoid pitfalls in his own work? -LD

(i) A rigorous mathematical framework can be helpful in understanding things that one can do or cannot do. This might save time in searching for something that is impossible to do. (ii) Early works by great mathematicians can also be very helpful in solving difficult engineering problems once these engineering problems are formulated as mathematical problems.

7) Where will be your future research heading in the next two years? Would you please provide a few references in this direction? -LD

We are extending our research interest from *networking* to *network science*. Network science

## IEEE COMSOC TCCN Newsletter

and big data analytics are receiving tremendous interest. There are many open and challenging problems in these emerging fields. Currently, we focus on the problem of structural analysis and community detection in large networks. Here are the pointers for two of our recent works:

1. Cheng-Shang Chang, Chih-Jung Chang, Wen-Ting Hsieh, Duan-Shin Lee, Li-Heng Liou, and Wanjiun Liao, "Relative centrality and local community detection," *Network Science*, vol. 3, no. 4, pp. 445-479, December 2015.

2. Cheng-Shang Chang, Wanjiun Liao, Yu-Sheng Chen and Li-Heng Liou, "A mathematical theory for clustering in metric spaces," accepted by *IEEE Transactions on Network Science and Engineering*.



**Cheng-Shang Chang** (S'85-M'86-M'89-SM'93-F'04) received the B.S. degree from National Taiwan University, Taipei, Taiwan, in 1983, and the M.S. and Ph.D. degrees from Columbia University, New York, NY, USA, in 1986 and 1989, respectively, all in Electrical Engineering. From 1989 to 1993, he was employed as a Research Staff Member at the IBM Thomas J. Watson Research Center, Yorktown Heights, N.Y. Since 1993, he has been with the Department of Electrical Engineering at National Tsing Hua University, Taiwan, R.O.C., where he is a Tsing Hua Chair Professor. His current

research interests are concerned with network science, high speed switching, communication network theory, and mathematical modeling of the Internet. Dr. Chang received an IBM Outstanding Innovation Award in 1992, an IBM Faculty Partnership Award in 2001, and Outstanding Research Awards from the National Science Council, Taiwan, in 1998, 2000 and 2002, respectively. He also received Outstanding Teaching Awards from both the college of EECS and the university itself in 2003. He was appointed as the first Y. Z. Hsu Scientific Chair Professor in 2002 and elected to an IEEE Fellow in 2004. Dr. Chang received the Academic Award from the Ministry of Education and the Merit NSC Research Fellow Award from the National Science Council in 2011. He is the author of the book "Performance Guarantees in Communication Networks" and the coauthor of the book "Principles, Architectures and Mathematical Theory of High Performance Packet Switches." He served as an editor for Operations Research from 1992 to 1999 and an editor for IEEE/ACM Transactions on Networking from 2007 to 2009. He is currently serving as an editor-at-large for IEEE/ACM Transactions on Networking and an editor for IEEE Transactions on Network Science and Engineering. Dr. Chang is a member of IFIP Working Group 7.3.

An Interview with Dr. Zhu Han on Cognitive Radio VANETs

1) Could you briefly introduce the most significant work that you have contributed to the cognitive networks research in the past three years? - LD

T Wang, L Song, Z Han, "Coalitional graph games for popular content distribution in cognitive radio VANETs," *IEEE Transactions on Vehicular Technology*, 62 (8), pp. 4010-4019, 2013.

First the application, we extended cognitive radio networking to vehicular networks for better spectrum usage. The resource allocation is based on coalitional graph game, which can conduct distributed and structured optimization.

2) What would you say is the most unique and impressive aspect of this work? - LD

Typical coalitional game has no internal structure. The proposed graph coalitional game can have such a structure that can represent some concepts such as cluster head etc. This is one a few work in the literature with such a capability, which fits many varieties of applications.

3) How did you come to those groundbreaking findings? - LD

It is not ground breaking. Instead we find one of better tools for distributed resource allocation which can overcome the previous tools' limitation. Then we provide solutions on one of the most popular networks.

4) What were the main challenges that you had to overcome? -LD

The convergence proof of the proposed schemes need a lot of novel concepts which are unknown to the society. Also when applied to VANET, the setup requires a lot of efforts.

5) How does that have implications for the real world? -LD

For the future VANETs, the connections between the vehicles are requested. Moreover, for some tasks such as data dissemination, driving safety, etc., it needs cooperation in VANETs. Such a proposed idea can facilitate the

future distributed network design for large VANETs.

6) Would you please describe the lessons you learned to help the reader avoid pitfalls in his own work? -LD

Try to go to conference, discuss with others, give talks. Sometime constructive comments are most valuable for researchers and should be appreciated.

7) Where will be your future research heading in the next two years? Would you please provide a few references in this direction? -LD

For big data analysis, smart grid for large fleets of electrical and self driving vehicles, and privacy/security in such networks.



**Zhu Han** received the B.S. degree in electronic engineering from Tsinghua University, in 1997, and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Maryland, College Park, in 1999 and 2003, respectively.

From 2000 to 2002, he was an R&D Engineer of JDSU, Germantown, Maryland. From 2003 to 2006, he was a Research Associate at the University of Maryland. From 2006 to 2008, he was an assistant professor at Boise State University, Idaho. Currently, he is a Professor in the Electrical and Computer Engineering Department as well as in the Computer Science Department at the University of Houston, Texas.

## **IEEE COMSOC TCCN Newsletter**

His research interests include wireless resource allocation and management, wireless communications and networking, game theory, big data analysis, security, and smart grid. Dr. Han received an NSF Career Award in 2010, the Fred W. Ellersick Prize of the IEEE Communication Society in 2011, the EURASIP Best Paper Award for the Journal on Advances in Signal Processing in 2015, IEEE Leonard G. Abraham Prize in the field of Communications Systems (best paper award in IEEE JSAC) in 2016, and several best paper awards in IEEE conferences. Currently, Dr. Han is currently an IEEE Communications Society Distinguished Lecturer.

## An Interview with Dr. Mihaela van der Schaar on Multi-agent Learning and Decision Making

1) Could you briefly introduce the most significant work that you have contributed to the cognitive networks research in the past three years? - LD

(MvdS) I believe the most important work of my group and I in the past 3 years is the development of theoretical foundations, methods and systems enabling intelligent use of available data (network data, consumer data, application data etc.) to learn and make decisions. This involves decisions on which information to acquire, how to use the information acquired to learn and make decisions, how current decisions affect long-run performance, and how to learn from and interact with other users. I often call this developing the Science of Data Science.

2) What would you say is the most unique and impressive aspect of this work? - LD

(MvdS) The most unique aspect of this work is developing new methods and algorithms for multi-agent cognition, learning and decision making for a variety of environments, exhibiting unique features (e.g. highly dynamic, heterogeneous, strategic) and special constraints (e.g. delay, resources, informational, various inter-user couplings).

3) How did you come to those groundbreaking findings? - LD

(MvdS) We developed new theory and methods which build on concepts from machine learning, information processing, optimization and decision making, as well as game theory and added new concepts and dimensions. For instance, our work on distributed machine learning is able to effectively mine (complex, multi-modal) data in real time, from multiple dispersed locations, and to make timely decisions about what and from whom to learn, how much money/effort/time to expend in learning, and how to trade off accuracy and timeliness of decisions.

4) What were the main challenges that you had to overcome? -LD

(MvdS) Multi-agent learning and decision making is not simply solving a set of (tightly or loosely) coupled learning or optimization problems. It requires solving new challenges such as understanding how the learning of an agent influences and it is influenced by another agents' learning, (possible strategic) behavior, informational monitoring abilities etc. etc. Another challenge is that solving correctly such problems requires going beyond one's own expertise and comfort zone and understand methods and solutions related to the considered problem which come from different fields, which have their own formalisms, terminology and methods.

5) How does that have implications for the real world? -LD

(MvdS) The methods which we developed are useful and powerful in many applications – medicine, (cognitive) communications, networks, network science, smart grids, crowdsourcing, as well as education. For just one example: our methods are providing better methods for breast cancer screening, diagnosis and treatment.

6) Would you please describe the lessons you learned to help the reader avoid pitfalls in his own work? -LD

(MvdS) I have learned that one often underestimates the challenges associated with displacing an existing technology (even if the gains obtained by the new technology are huge) as well as explaining new technology to practitioners in a way which is accessible to them, such that new technologies can find their place into new products.

7) Where will be your future research heading in the next two years? Would you please provide a few references in this direction? -LD

(MvdS) My research in the near future is dedicated to developing new data science, machine learning and decision making methods for medicine and finance. These are 2 application domains to which we are devoting our attention.

## IEEE COMSOC TCCN Newsletter

To get a better idea about our recent work, its relationship to cognitive communications, as well as some of our recent work, see the following papers below.

M. van der Schaar, Y. Xiao, W. Zame, "Efficient Outcomes in Repeated Games with Limited Monitoring," *Economic Theory*, vol. 60, no. 1, pp. 1-34, 2015 - Lead article. [[Link](#)]

C. Tekin and M. van der Schaar, "Distributed Online Learning via Cooperative Contextual Bandits," *IEEE Trans. Signal Process.*, vol. 63, no. 14, pp. 3700-3714, 2015. [[Link](#)]

Y. Song and M. van der Schaar, "Dynamic Network Formation with Incomplete Information," *Economic Theory*, vol. 59, no. 2, pp. 301-331, 2015. [[Link](#)]

A. M. Alaa, J. Yoon, S. Hu, M. van der Schaar, "Personalized Risk Scoring for Critical Care Patients using Mixtures of Gaussian Process Experts," *ICML 2016 - Workshop on Computational Frameworks for Personalization.*, 2016. [[Link](#)]



**Mihaela van der Schaar** is Chancellor's Professor of Electrical Engineering at University of California, Los Angeles. She is an IEEE Fellow (since 2009), was a Distinguished Lecturer of the Communications Society (2011-2012), and the Editor in Chief of IEEE Transactions on Multimedia (2011-2013). She also is the director and founder of UCLA Center for Engineering Economics, Learning and Networks.

**An Interview with Dr. Narayan Mandayam on Prospect Pricing in CRNs**

1) Could you briefly introduce the most significant work that you have contributed to the cognitive networks research in the past three years? - LD

(NM) The most significant work would be modeling the role of end-user behavior, and its impact on resource allocation in cognitive radio networks as well as dynamic pricing. Specifically, Prospect Theory, a Nobel Prize winning theory that explains real-life decision-making and its deviations from Expected Utility Theory (EUT) behavior is used in the study and design of wireless networks. The following papers from our research group which includes collaboration with Dr. Arnold Glass (a cognitive psychologist at Rutgers) provide a good perspective of this work:

[1] Y. Yang, L. Park, N. B. Mandayam, I. Seskar, A. Glass, and N. Sinha, "Prospect Pricing in Cognitive Radio Networks," in IEEE Transactions on Cognitive Communication Networks, vol. 1, No. 1, pp. 56-70, March 2015  
[2] T. Li and N. B. Mandayam, "When Users Interfere with Protocols: Prospect Theory in Wireless Networks using Random Access and Data Pricing as an Example," in IEEE Transactions on Wireless Communications, 13(4):1888-1907, April 2014

2) What would you say is the most unique and impressive aspect of this work? - LD

(NM) Working in collaboration with cognitive psychologists and using data collected from human-subject studies on video QoS to build models for use in resource allocation strategies is unique. Policing mechanisms in RRM that influence wireless device behavior and thereby drive systems to better operating points essentially are borne out of EUT based microeconomics approaches, and implemented via engineered system design, i.e., embedding these strategies in the link layer and network layer protocols that are executed by wireless devices. When a service provider controls access to end-users via differentiated and hierarchical monetary pricing, then the performance of the network is directly subject to end-user decision-making that deviates from EUT. In fact, our results show that, when the end-users underweight the service guarantee, they tend to reject

the offer, which results in under-utilization of radio resources and revenue loss. We propose prospect pricing, a pricing mechanism that can make the system robust to decision making and improve RRM.

3) How did you come to those groundbreaking findings? - LD

(NM) Using a mix of theory, algorithm development and experimentation with human subjects with video QoS, our research seeks to design and study wireless network pricing and the psychophysical relationship between QoS and QoE from a cognitive psychology perspective, thereby presenting a novel framework to understand how wireless network performance can be influenced by end-user behavior and vice-versa.

4) What were the main challenges that you had to overcome? -LD

(NM) Including human-subject studies in theoretical and analytical RRM work is a challenge in itself. Overcoming the research barriers and working with cognitive psychologists so as to convey the bigger picture of what we are trying to do has been very rewarding.

5) How does that have implications for the real world? -LD

(NM) There is a recognition and push in both industry and academia towards the goal of achieving "1000x" capacity for wireless. The solution approaches range from spectrally agile cognitive radios with novel spectrum sharing, to use of higher frequency spectrum as well as smaller and denser cell deployments. While this is a much needed activity with many challenges to overcome, providing a spatially high density of wireless/wired backhaul is expensive and the overwhelming demands on wireless capacity fundamentally remain, in that state-of-the-art systems are nowhere near the 1000x capacity target goals and perhaps even an order of magnitude or two away. As a result, wireless service providers in recent times have resorted to control access and services being provided to end-users via differentiated and hierarchical monetary pricing. The complementary approach

## IEEE COMSOC TCCN Communications

termed “prospect pricing” that is proposed in our work is a way to support data demand and relies on influencing end-user (human) behavior using dynamic pricing algorithms when technological solutions by themselves cannot satisfy the demands of wireless data.

6) Would you please describe the lessons you learned to help the reader avoid pitfalls in his own work? -LD

(NM) When working on truly interdisciplinary research that breaks new ground, one needs to have reliable collaborators and a lot of patience to overcome any roadblocks along the way. This includes working hard towards understanding each other’s work, having an open mind and not being afraid to ask seemingly dumb questions. It also helps to have funding to support such new crosscutting ideas! We thank the NSF Nets Program for enabling this research under award number 1421961.

7) Where will be your future research heading in the next two years? Would you please provide a few references in this direction? -LD

(NM) After our initial work pointing out the role Prospect Theory can play in wireless networking research, the applications of this theory has really caught on and taken off along many new directions. Most recently, there has been work on applications such as those related to the smart grid, security and privacy. An example of this work would be the following paper that appeared in the IEEE Proceedings:

[3] W. Saad, A. Glass, N. B. Mandayam, and H. V. Poor, “Toward a Consumer-Centric Grid: A Behavioral Perspective,” in Proceedings of the IEEE, vol. 104, No. 4, pp. 865-882, April 2016



**Narayan B. Mandayam** is a Distinguished Professor and Chair of Electrical and Computer Engineering at Rutgers University, where he also

serves as Associate Director of the Wireless Information Network Laboratory (WINLAB). He received the B.Tech (Hons.) degree in 1989 from the Indian Institute of Technology, Kharagpur, and the M.S. and Ph.D. degrees in 1991 and 1994 from Rice University, all in electrical engineering. Dr. Mandayam’s research interests are in various aspects of wireless data transmission with emphasis on techniques for cognitive radio and software defined networks including their implications for spectrum policy. Using constructs from game theory, communications and networking, his work has focussed on system modeling and performance, signal processing as well as radio resource management for enabling wireless technologies to support various applications. He has also been working recently on aspects related to wireless backhaul, small cells, noncontiguous spectrum access, visual MIMO networks and the use of prospect theory in understanding the psychophysics of data pricing for wireless networks as well as the smart grid. His recent interests also include privacy in IoT as well as modeling and analysis of trustworthy knowledge creation on the internet.

Dr. Mandayam is a co-recipient of the 2015 IEEE Communications Society Advances in Communications Award for his seminal work on power control and pricing, the 2014 IEEE Donald G. Fink Award for his IEEE Proceedings paper titled “Frontiers of Wireless and Mobile Communications” and the 2009 Fred W. Ellersick Prize from the IEEE Communications Society for his work on dynamic spectrum access models and spectrum policy. He is also a recipient of the Peter D. Cherasia Faculty Scholar Award from Rutgers University (2010), the National Science Foundation CAREER Award (1998) and the Institute Silver Medal from the Indian Institute of Technology (1989). He is a coauthor of the books: Principles of Cognitive Radio (Cambridge University Press, 2012) and Wireless Networks: Multiuser Detection in Cross-Layer Design (Springer, 2004). He has served as an Editor for the journals IEEE Communication Letters and IEEE Transactions on Wireless Communications. He has also served as a guest editor of the IEEE JSAC Special Issues on Adaptive, Spectrum Agile and Cognitive Radio Networks (2007) and Game Theory in Communication Systems (2008). He is a Fellow of the IEEE and has a served as a Distinguished Lecturer of IEEE COMSOC.

**An Interview with Dr. K.P. (Suba) Subbalakshmi on Cognitive Cloud Offloading**

1) Could you briefly introduce the most significant work that you have contributed to the cognitive networks research in the past three years? - LD

(KPS) I have recently become interested in the confluence of mobile computing on the one hand and advances in cognitive networks on the other. I have been working on efficient ways to manage computational and other resource demands on the mobile devices under the reality of growing traffic load on the wireless backhaul. We call this approach Cognitive Cloud Offloading. Traditionally, when the mobile applications got too complex and resource hungry, these were either offloaded wholly or partially to a resource-rich remote entity (say a cloud). We extend this concept to the current state-of-the art in wireless devices which uses multi-RAT technologies and several dynamic spectrum management concepts like bandwidth aggregation. Another difference between this work and several existing works is that we also approach it from the applications perspective. Rather than using a compiler imposed scheduling of execution for the components in the application, we allow for our solution to find the optimal scheduling order (along with optimizing over all multi-RAT interfaces and the usual parameters like energy and delay) for the individual components in the application, keeping natural dependencies as well as the wireless network conditions in mind. This is, therefore, a multi-disciplinary, holistic solution that provides greater degrees of freedom in the solution space and hence offers the potential for better overall trade-offs.

2) What would you say is the most unique and impressive aspect of this work? - LD

(KPS) The unique and interesting aspect of this work lies in the fact that this class of approaches actively uses the latest advancements in the wireless world (bandwidth aggregation, multi-RAT technologies) etc. in the mobile computing and becomes very relevant under the current advances in edge computing and fog computing.

3) How did you come to those groundbreaking findings? - LD

(KPS) We originally started with trying to use the latest in cognitive networking to solve

problems in delivering sophisticated mobile applications to the consumer. As we went through the process we realized that most approaches to offloading assume a compiler pre-determined order of scheduling, which means that several opportunities for parallel processing were being missed. We decided to then to investigate a truly inter-disciplinary approach to solve this problem.

4) What were the main challenges that you had to overcome? -LD

(KPS) The biggest technical challenges are in finding a good mathematical formulation (or model) for the various trade-offs that exists in an optimization problem of this scale, finding efficient ways to solve these optimization problems and finding algorithms that can implement these solutions. For instance, background traffic in the mobile device, the energy expended and saved in the mobile device, the interactions of various constraints on the components so that the natural execution order is not compromised, while delay conditions are being met, must all be modeled mathematically. The second challenge is to find efficient ways to solve this optimization problem so that it can be implemented successfully.

5) How does that have implications for the real world? -LD

(KPS) These solutions will effectively impact the user experience positively in the mobile applications space. For example, applications like virtual reality, 3D interactive games, mobile health care, mobile disaster response, will all work faster and more efficiently and will feel more real-time when these solutions are implemented.

6) Would you please describe the lessons you learned to help the reader avoid pitfalls in his own work? -LD

(KPS) One of the key lessons we learnt along the way is to first mathematically model the problem and the constraints and then solve it, then cross verify the models and solutions using experimental data from mobile devices to fine-tune the model and make sure that the mathematics matches the reality. The theory-

## IEEE COMSOC TCCN Newsletter

implementation loop needs to be closed several times along the way, especially to have an impact on Industry.

7) Where will be your future research heading in the next two years? Would you please provide a few references in this direction? -LD

(KPS) Our team is continuing this line of inquiry to more sophisticated real life scenarios including, the Internet of Things, mobile health care and disaster preparedness, smart and connected communities etc. We are also working on commercializing these ideas via [Spectronn](#), a technology start-up company that I have co-founded. Spectronn provides solutions in the software defined cognitive wireless networking space.

Some examples of our work can be found here:

1. Syed Eman Mahmoodi and K.P. Subbalakshmi, "A Time-Adaptive Heuristic for Cognitive Cloud Offloading in Multi-RAT Enabled Wireless Devices," IEEE Transactions on Cognitive Communications and Networking , vol.PP, no.99, pp.1-1, July 2016.
2. Syed Eman Mahmoodi, K.P. Subbalakshmi and R.N.Uma, "Harnessing Spectrum Awareness to Enhance Mobile Computing", IEEE The 22nd International Conference on Mobile Computing and Networking (Mobicom) 2016
3. S. E. Mahmoodi; R. N. Uma; K. P. Subbalakshmi, "Optimal Joint Scheduling and Cloud Offloading for Mobile Applications," in IEEE Transactions on Cloud Computing, vol.PP, no.99, pp.1-1, April 2016.
4. Syed Eman Mahmoodi and K.P. Subbalakshmi, "Cognitive cloud off-loader: Real-time method for joint scheduling offloading computation in Multi-RAT enabled mobile devices", Provisional Patent Filed, December 2015.
5. Syed Eman Mahmoodi, K.P. Subbalakshmi and Vidya Sagar, "Cloud Offloading for Multi-Radio Enabled Mobile Devices", IEEE International Conference on Communications, London, June 2015, pp. 5473-5478.



**K.P. (Suba) Subbalakshmi** is a Professor in the Department of ECE at Stevens Institute of Technology. She is also the Co-founder of two technology start-up companies, [Spectronn](#) and [Jaasuz](#). Her research interests are in Cognitive Radio Networking, Cognitive Cloud Computing, Dynamic Spectrum Access security, Social Media Analysis and Forensics and their applications to smart cities and connected communities.

She was named a Jefferson Science Fellow in 2016. As a Jefferson Science Fellow, she will be a Senior Technical Advisor with the US Department of State, Bureau of Economic and Business Affairs, the Deputate of International Communications and Information Policy, Office of Multilateral Affairs (EB/CIP/MA). She served as a Subject Matter Expert for the National Spectrum Consortium in 2015. She is a Founding Associate Editor of the IEEE Transactions on Cognitive Communications and Networking. She is the Founding Chair of the Special Interest Group on Security, IEEE COMSOC's Technical Committee on Cognitive Networks. She is a recipient of the New Jersey Inventors Hall of Fame, Innovator Award. Her research is supported by NSF, NIJ, AFRL, US ISSO, Industry and other DoD agencies. Suba received her PhD in Engineering Science from the Simon Fraser University, Canada; her M.E in Electrical Communication Engineering from the Indian Institute of Science, Bangalore and her B.Sc in Physics from the University of Madras.

**An Interview with Dr. Ranveer Chandra on TV White Space Networks**

1) Could you briefly introduce the most significant work that you have contributed to the cognitive networks research in the past three years? - LD

My most significant contribution in cognitive network research in the past three years is probably the realization of TV White Space networks in different parts of the world, such as in Africa and India. We have been connecting schools, hospitals and villages with this technology.

2) What would you say is the most unique and impressive aspect of this work? - LD

This is a systems research with huge impact. We get encouraging emails from people who previously were not connected to the Internet, or who had never seen a computer, about how this connectivity has helped improve their lives. People in Kenya who no longer have to commute all the time, or students in India who can now get access to the latest in education. This impact of our research is probably the most impressive part of this research. Of course behind this social impact is the huge research impact. We have demonstrated that the research that we, and the TCCN community, have been doing for over 10 years is actually feasible, and that Dynamic Spectrum Access Techniques actually work. We haven't received any complaint of interference with this technology in any of our deployments, starting with the first one in Microsoft campus in 2009.

3) How did you come to those groundbreaking findings? - LD

We started building the TV White Space networks in 2009. Back then, when most research was focused on simulations, I proposed that we actually build an actual network out to show that this technology can actually work in the wild. Along with my colleagues in MSR, we built the first outdoor TV white space network in Microsoft campus, where we connected a campus shuttle to the Internet, and showed high speed continuous throughput over one mile of the campus, while the system caused no interference to TVs or wireless microphones. We demonstrated this system to the FCC Chairman

in 2010. Since then, we have more confidence in the robustness of this technology. In my opinion, the TV White Spaces provides an inexpensive last-mile technology that is also very useful as point-to-multipoint technology in the developing world. In 2012, I started working with Paul Garnett from Microsoft towards deployments of TV White Space Networks in Africa, and along with Sid Roberts we set up the networks there. We have explained these networks in the IEEE LANMAN 2015 paper. Then with Prashant Shukla, the Microsoft NTO in India, I helped set up the first TV White Space network in India in 2015. In the first network in India, we connected 5 remote schools to the Internet in a partnership with ERNET in India.

4) What were the main challenges that you had to overcome? -LD

The initial challenge was to convince the broadcasters that this technology as robust and it would not cause any interference to the reception of TV signals. We successfully overcame this challenge. Another challenge is to adapt to the requirements of each country. For example, when working with Singapore, I had to customize the database rules several times to meet the constraints of the government agency in Singapore (IDA), such as how to coexist with bordering countries.

5) How does that have implications for the real world? -LD

About half of the world's population is not connected to the Internet. In places where people are in the lower economic segment live, we need inexpensive technologies to help connect them to the Internet. This is where the TV White Spaces, or other Dynamic Spectrum Access technologies, can help. In the IEEE LANMAN 2015 paper we compare the cost of a TV White Spaces network with an LTE network, and show how this technology lowers the cost, even with current-day expensive radios. As the radio vendors recently announced in the DSA Conference in Columbia in May, 2016, the cost of the radios are expected to reduce drastically in the coming year. This should make these networks even more economical in the developing regions of the world. In our own deployments in Africa and

## IEEE COMSOC TCCN Newsletter

India, the biggest satisfaction comes from the complements we get from the people who are able to get connected, and who can now reap the benefits of connectivity. And I think, this is something that our entire TCCN research community should be proud of!

6) Would you please describe the lessons you learned to help the reader avoid pitfalls in his own work? -LD

I think the two lessons I have learnt are (i) to not be afraid of thinking big, and (ii) to have the patience and perseverance that eventually your vision will happen. Around 2009, a few friends suggested to move on to other research problems, but that is when I decided to start testing out these networks for real. These deployments are then what triggered these worldwide deployments of the TV White Space networks. It has taken time, but we have seen significant traction in different countries worldwide. That said, I still don't think we have achieved our vision yet. That will happen when we are able to connect most of the world's population, and I am hopeful it will happen soon.

7) Where will be your future research heading in the next two years? Would you please provide a few references in this direction? -LD

While I am continuing to help with TV White Space deployments in several countries, a new research project I have started at Microsoft Research is on an end-to-end IoT system for Agriculture. The goal is to enable data-driven farming to meet the growing food need of the world's population. We are using drones plus sensors to get data from the farms. However, most sensor solutions are currently expensive, since they use either cellular or satellite to get the data to the cloud. We are working on alternative solutions to bring down the cost of these sensors. Our key idea is to use the TV white spaces to get data from the sensors. Although there is not a lot of available TV white spaces spectrum in the cities, the rural areas have a lot of available TV spectrum. We could then set up long range IoT networks in the TV White Spaces to get the data from these sensors. Just like the Wi-Fi network

connects devices in your house, our vision is that the TV White Spaces will connect all sensors in the farm at a very low cost. We believe that with this technology, we can add a lot more sensors in the farm, and eventually help in increasing agricultural yield. You can learn more about this here: <http://research.microsoft.com/farmbeats>



**Ranveer Chandra** is a Principal Researcher at Microsoft Research. He is leading an incubation on IoT Applications, with a focus in Agriculture. He is also leading research projects on white space networking, low-latency wireless, and improving battery life of mobile devices. Ranveer has published more than 60 research papers and filed over 100 patents, 65 of which have been granted. His technology has shipped as part of Windows 7, Windows 8, Windows 10, XBOX, Visual Studio, and Windows Phone. Ranveer has won several awards, including the MIT Technology Review Top Innovators under 35 (TR35 2010), best paper awards at ACM CoNext 2008, ACM SIGCOMM 2009, IEEE RTSS, and USENIX ATC, the Microsoft Graduate Research Fellowship, and Fellow in Communications of the World Technology Network. He has also served as the Program Committee Chair of IEEE DySPAN 2012 and ACM MobiCom 2013. Ranveer has an undergraduate degree from IIT Kharagpur, India and a Ph.D. in Computer Science from Cornell University.

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